EUV - light for the nano-world

Larissa Juschkin

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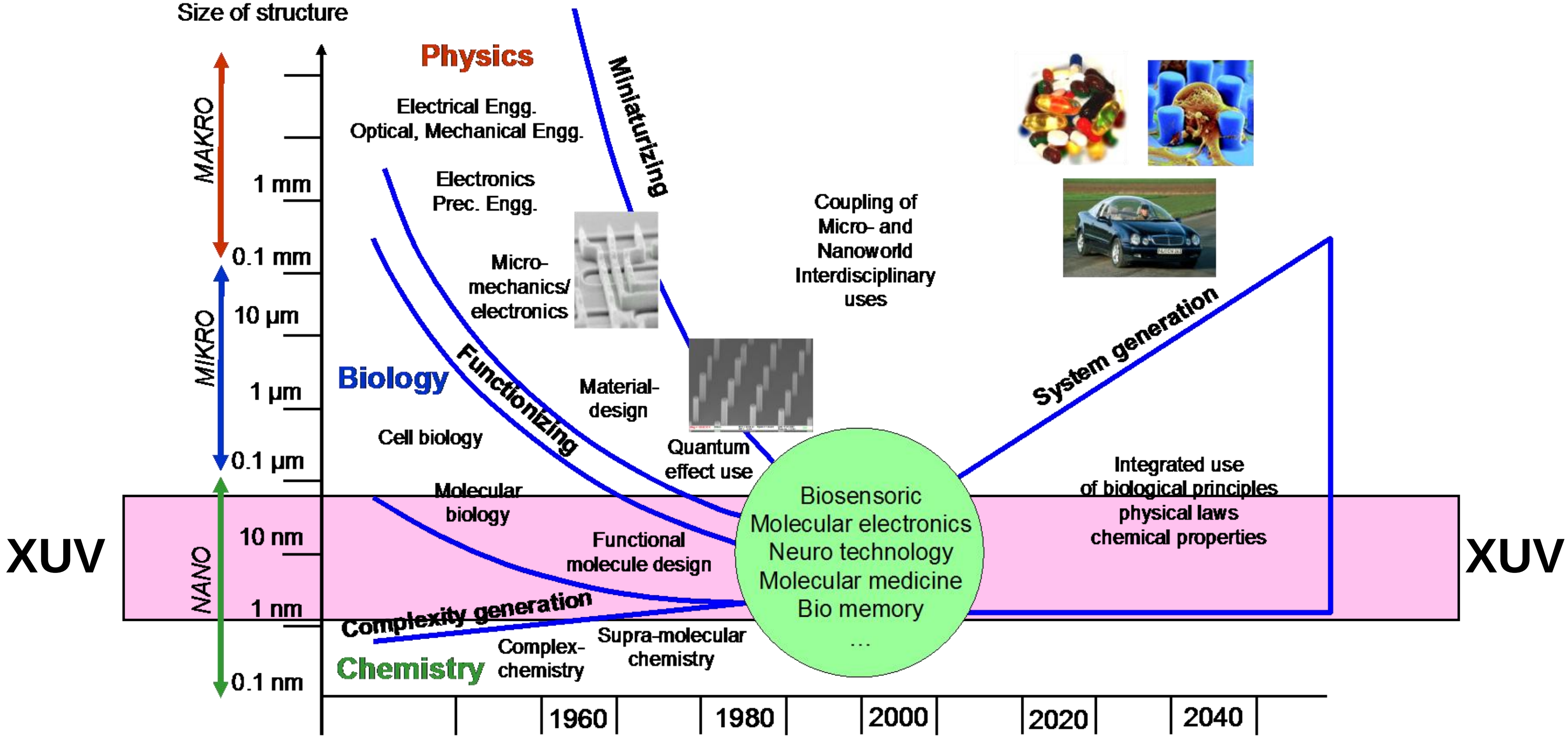
Nanotechnology

from: A. Zweck, Nanotechnologie: Technologiefrüherkennung, Innovationsmanagement und Perspektiven, (2006) available www.zukuenftigetechnologien.de or www.vditz.de



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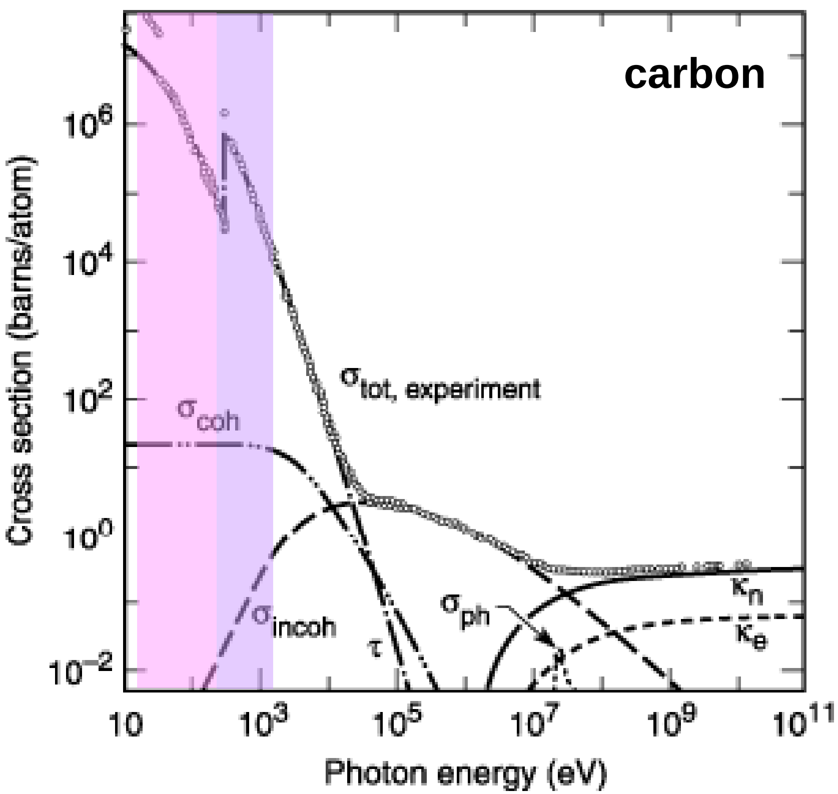
Interaction of XUV radiation with matter



Wavelength	2,3 nm < λ < 4,4 nm	λ > 5 nm
Penetration depth (1/e)	few μm	10 to 100 nm, for gases few mm

Dominating processes:
photo absorption and elastic scattering

Corresponding applications

- **absorption edge structure**
- **chemical analysis**
- **surface and thin film characterization**
- **microscopy with natural element contrast (water window) and high resolution**
- **structuring (lithography, waveguides, etc.)**
- **defect inspection with coherent scattering**
- **lens less imaging**

➢ **vacuum environment necessary**
➢ **thin films as filters and windows**
➢ **no refractive optics**

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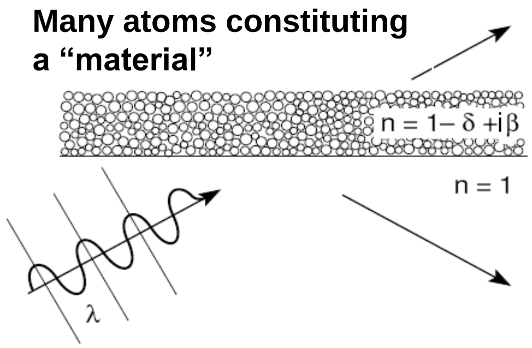
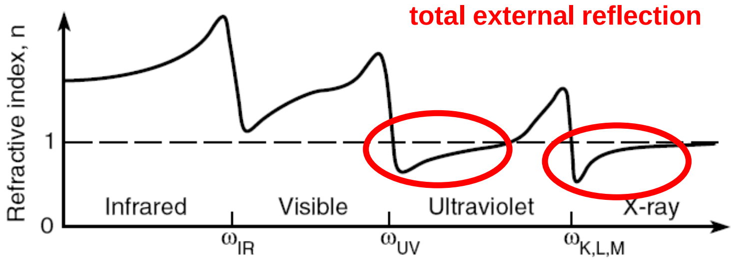
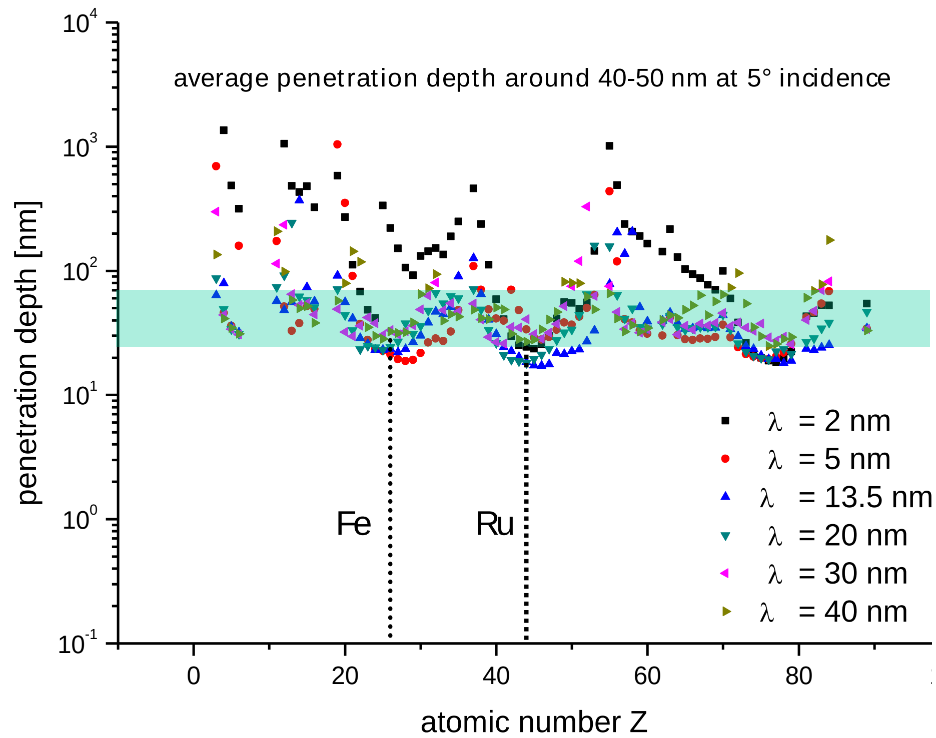
Index of refraction

$$n(\omega) = 1 - \frac{n_a r_e \lambda^2}{2\pi} \underbrace{\left(f_1^0 - i f_2^0\right)}_{\text{complex atomic scattering factor}} = 1 - \delta + i\beta$$

$$\mathbf{E}(\mathbf{r},t) = \underbrace{\mathbf{E}_0 e^{-i\omega(t-r/c)}}_{\text{vacuum propagation}} \underbrace{e^{-i(2\pi\delta/\lambda)r}}_{\phi\text{-shift}} \underbrace{e^{-(2\pi\beta/\lambda)r}}_{\text{decay}}$$







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Compromise between source characteristics and application needs

Given source characteristics

Spectral radiance:

radiation energy (photons) per time interval, wavelength, solid angle and area

polarization

emitting volume

coherence properties

Variety of application needs

spectral characteristics

spatial resolution

time resolution

irradiance

sensitivity

dose

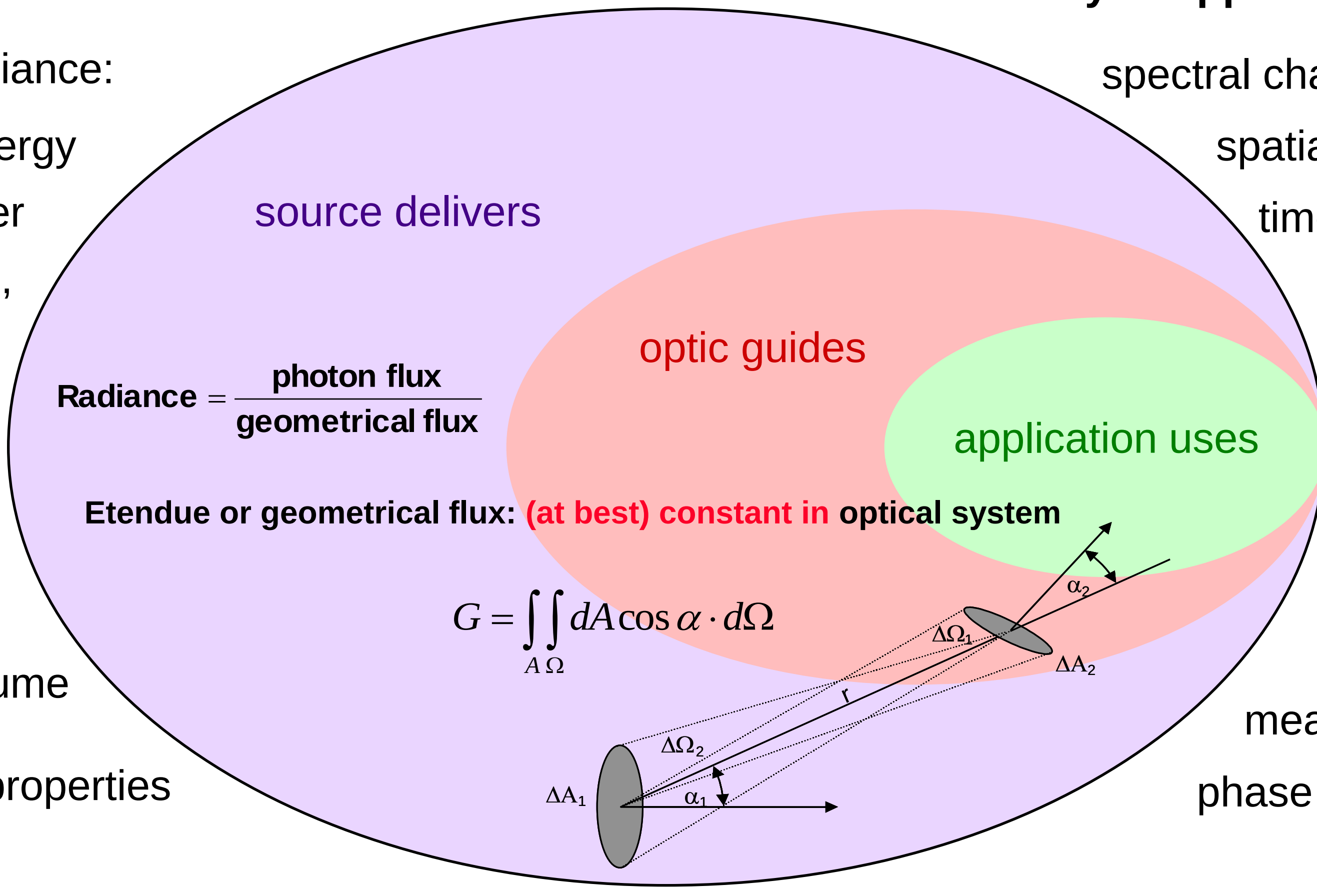
throughput

divergence

polarization

measuring spot

phase information



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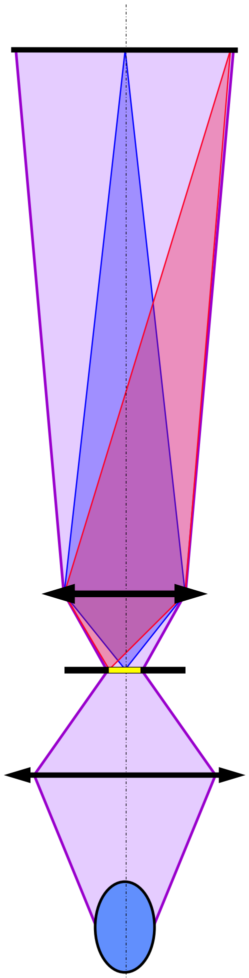
Source requirements for microscopy applications



NA = 0.61 x *λ/RES* ~ 0.2 – 0.3 needed for resolution
=> *Ω* = 0.1 – 0.5 sr radiation solid angle at sample

Magnification determined by resolution and detector pixel size
=> object field limitation through detector size and magnification

Etendue used by microscopy application ~ 10^{-7} – 10^{-5} cm^2sr

Available incoherent sources: 10^{-2} – 10^{-1} cm^2sr

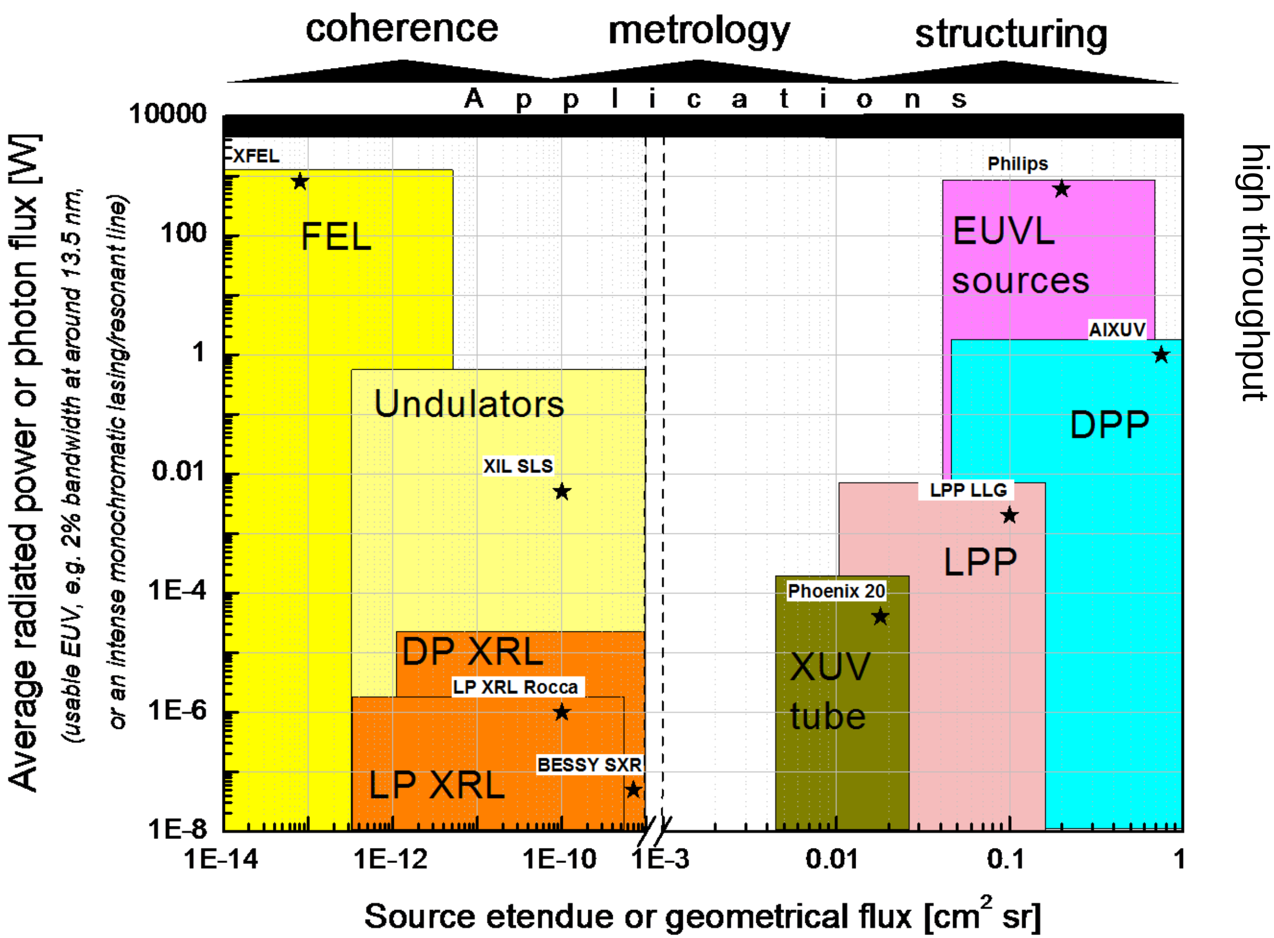
Synchrotron based sources and XRLs: < 10^{-9} cm^2sr

Necessary irradiation dose at sample is given by detector sensitivity, required signal dynamics, pixel size, magnification and transmission of imaging optics: 1 – 10 mJ/cm^2.

Minimal exposure time determined by CCD read-out speed

=> required average source radiance ~ 10^{-2} – 10^{-1} $W/(cm^2sr)$
within usable radiation bandwidth (one monochromatic line for zone plate or ~ 3 – 4 % for multilayer based optics)

Average power (of usable EUV) and etendue of different source concepts and existing sources



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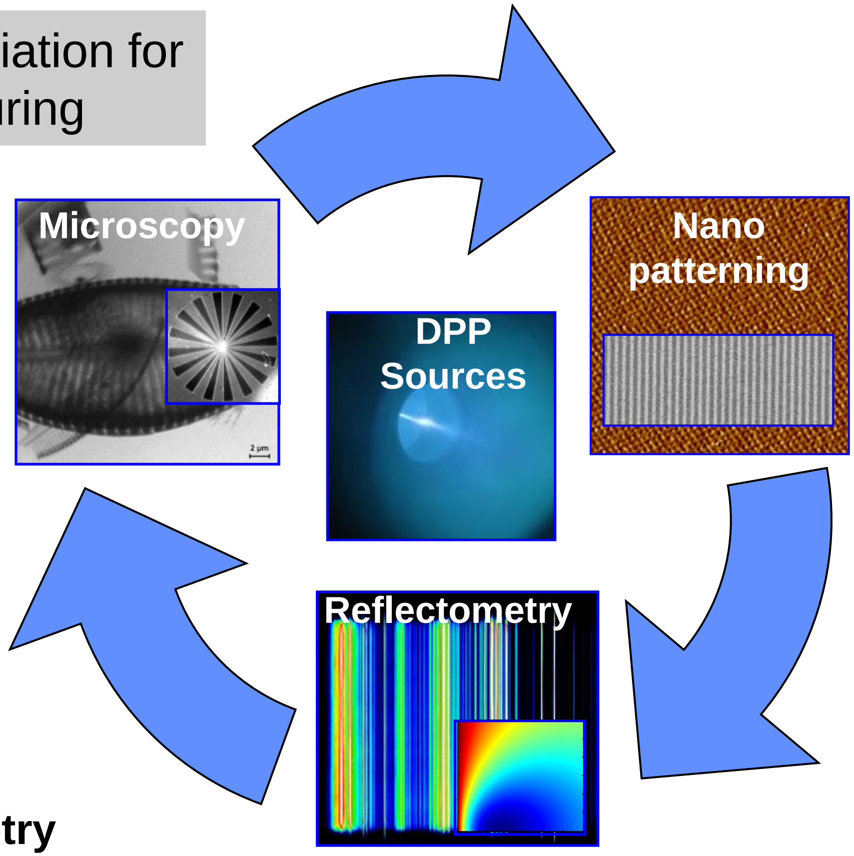
Research Activities of EUV Technology Group at TOS/ILT

Utilization of EUV radiation for metrology and structuring

Microscopy

- Defect detection
- EUV mask inspection
- Water window microscopy (ILT)

see „Moore"…



Lithography

- Nanostructuring of surfaces with laboratory sources
- Patterning of structures < 10 nm

write „Moore"…

Reflectometry

- Analysis of nanolayers and surfaces
- Layer thickness and roughness measurement
- Elemental composition

analyze „Moore"…

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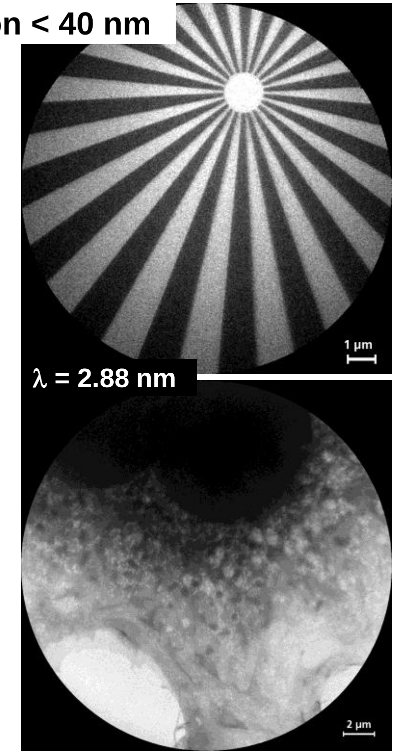
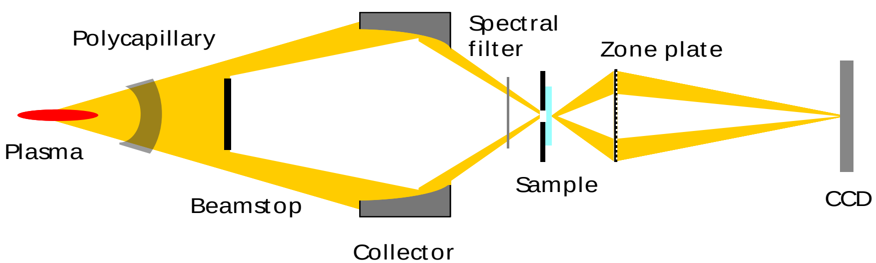
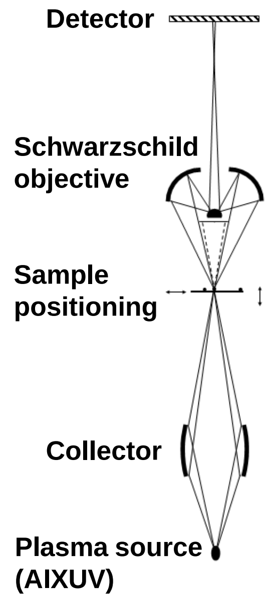
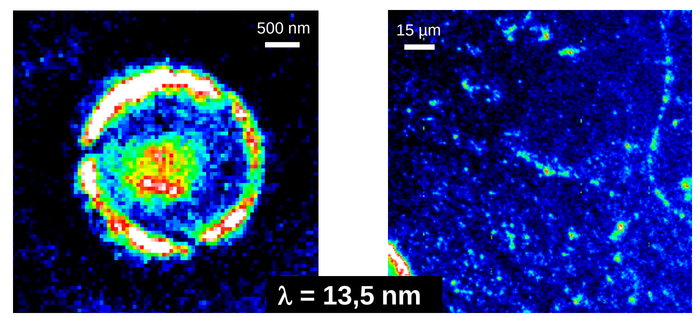
XUV-Microscopy at ILT / TOS

Resolution < 40 nm









Three 100 nm dots of transmission mask

Dark field image of nanoparticles D=112 nm

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Fraunhofer ILT

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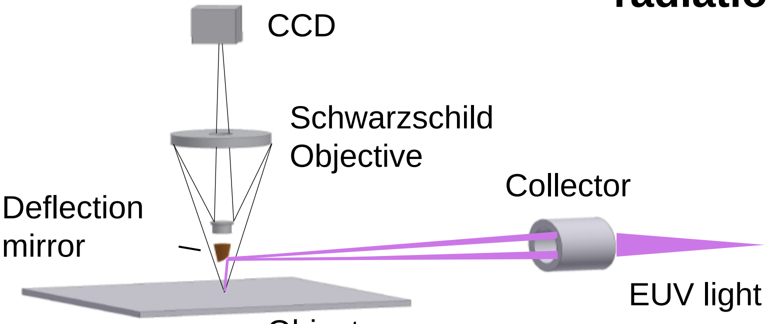
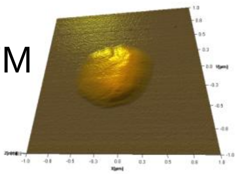
Mask blank inspection at TOS

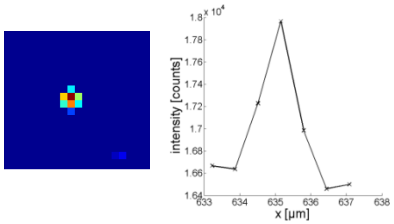


- Fundamental investigations on defect detection (influence of different kind of defects onto signal)
- Fast scanning of large surfaces – with 1 µm resolution and 10 nm sensitivity
- Design rules for an industrial mask blank inspection tool (source, optical system, detector, interaction of EUV radiation with a defect)

Natural defect:

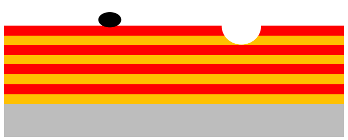
AFM

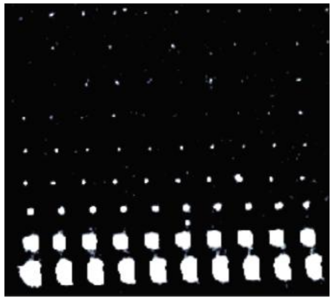




EUV - microscope

Structured bumps:





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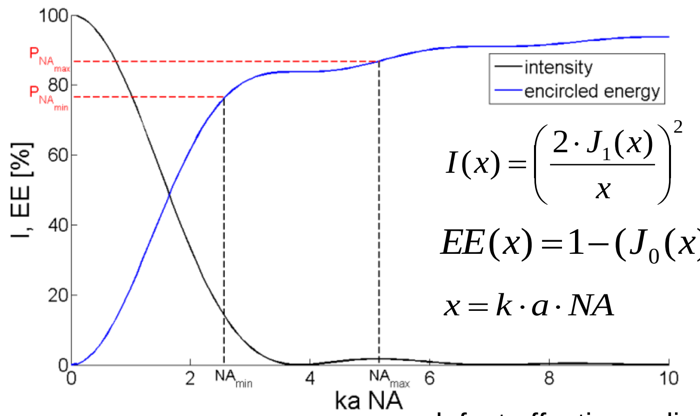
Detectable signal vs. defect size: pinhole approach

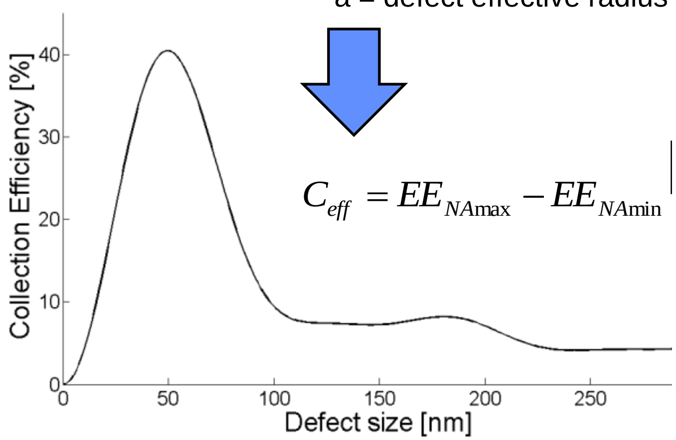


$$I(x)=\left(\frac{2\cdot J_1(x)}{x}\right)^2$$

$$EE(x)=1-(J_0(x))^2-(J_1(x))^2$$

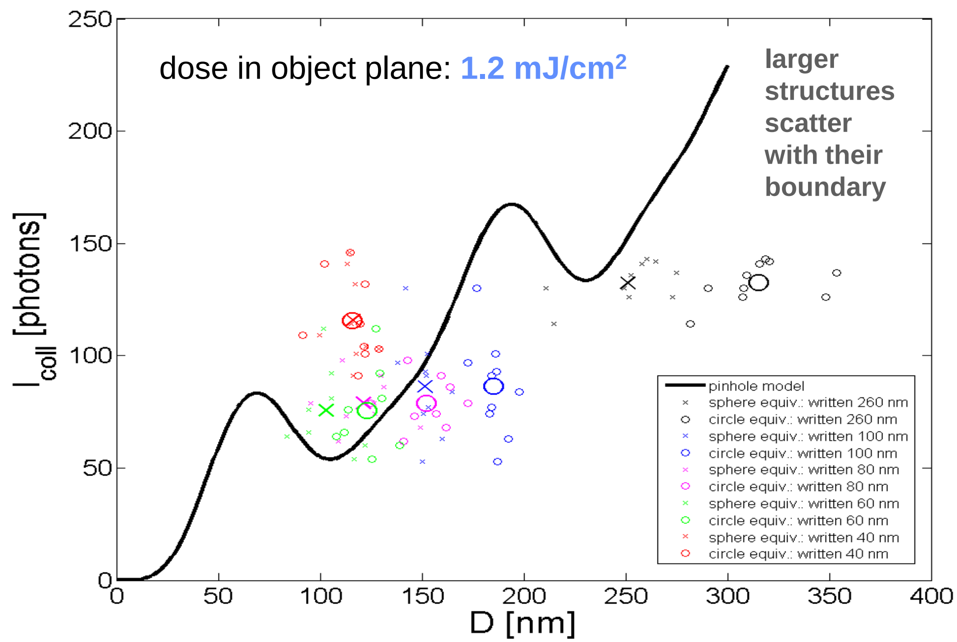
$$x=k\cdot a\cdot NA$$

a = defect effective radius



$$C_{eff}=EE_{NA\max}-EE_{NA\min}$$

Number of detectable photons as a function of defect size for 1 mJ/cm² dose in object plane



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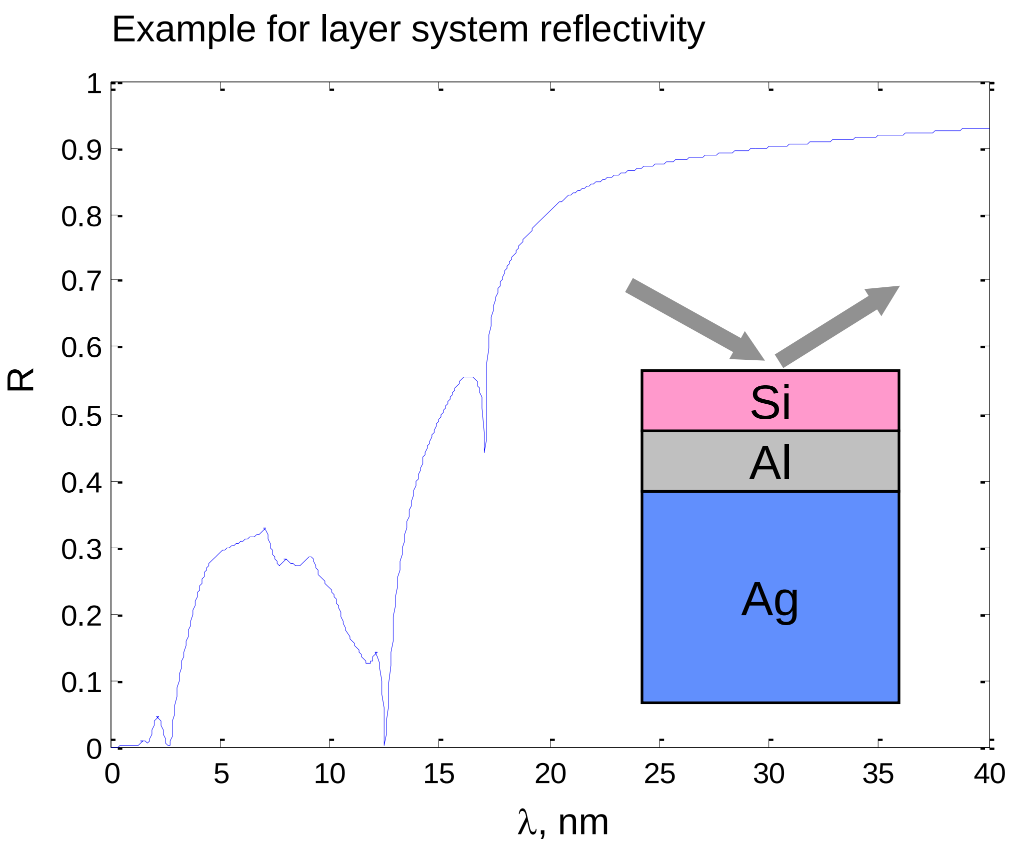
XUV reflectometry for surface analysis



Potential of XUV Reflectometry:

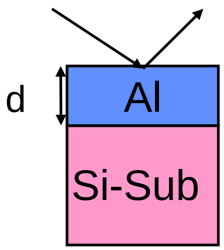
- **thin film analysis**
  (any material, similar n's in UV-VIS)
- **determination of chemical bonds**
  (near edge absorption fine structure)
- **surface sensitive technique**
  (penetration depth ~ 10 – 100 nm)
- **surface roughness determination**
  (smooth surface limit beyond VIS or UV)
- **high spatial resolution possible** ***(~1 µm)***
- **defect inspection** ***(„nano"-roughness in terms of spatial-frequency)***

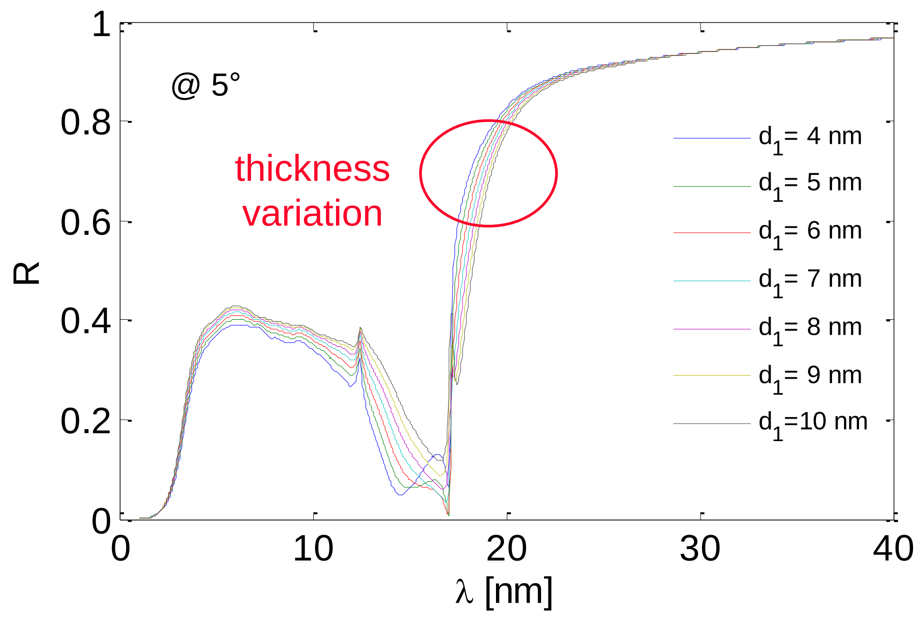
Quick Review: XUV Reflectometry

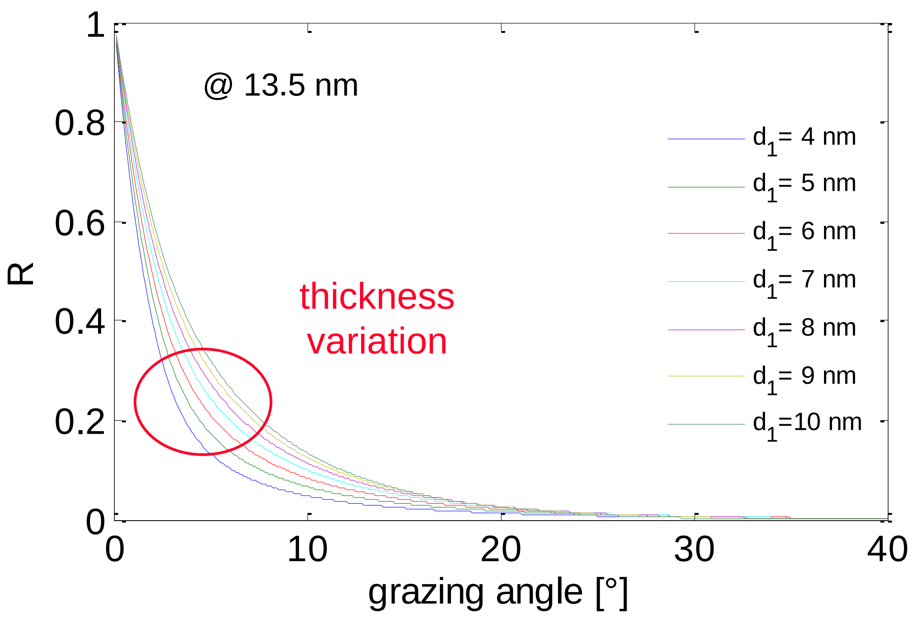
Reflectivity can be measured as:

1.Function of incident angle at fixed wavelength

2.Function of wavelength at fixed angle







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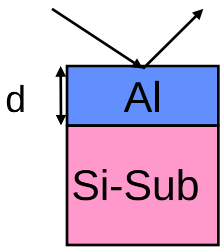

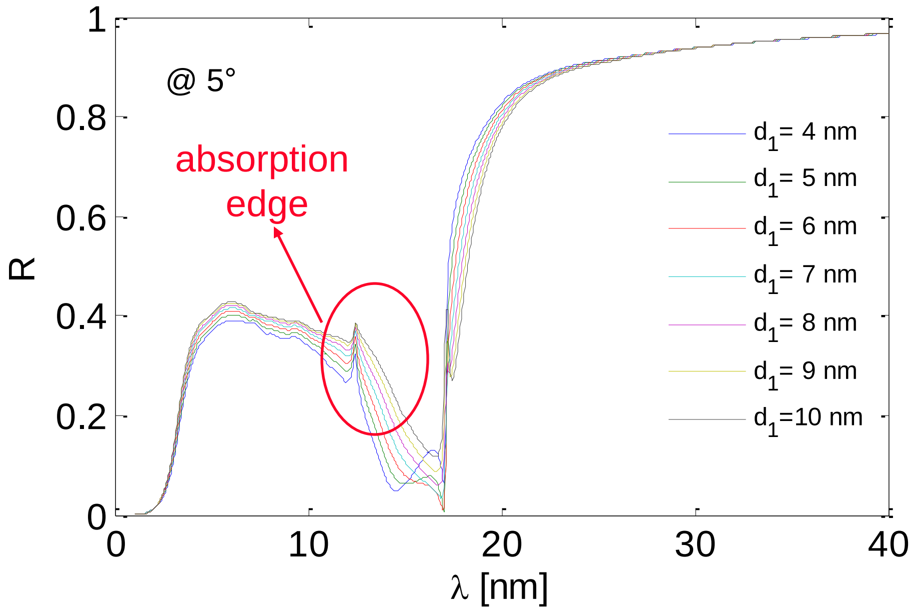

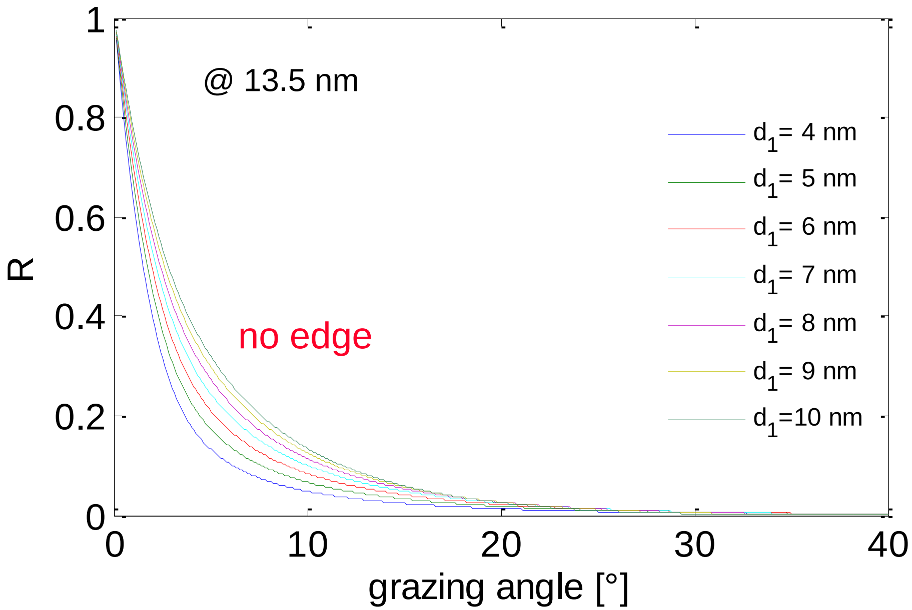

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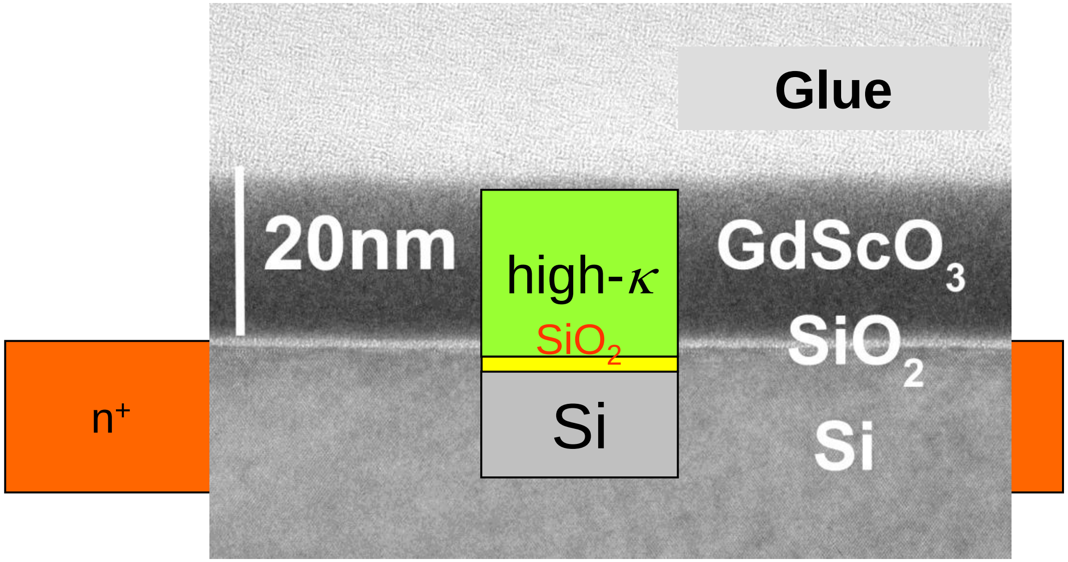
Application example „Parasitic“- Interface



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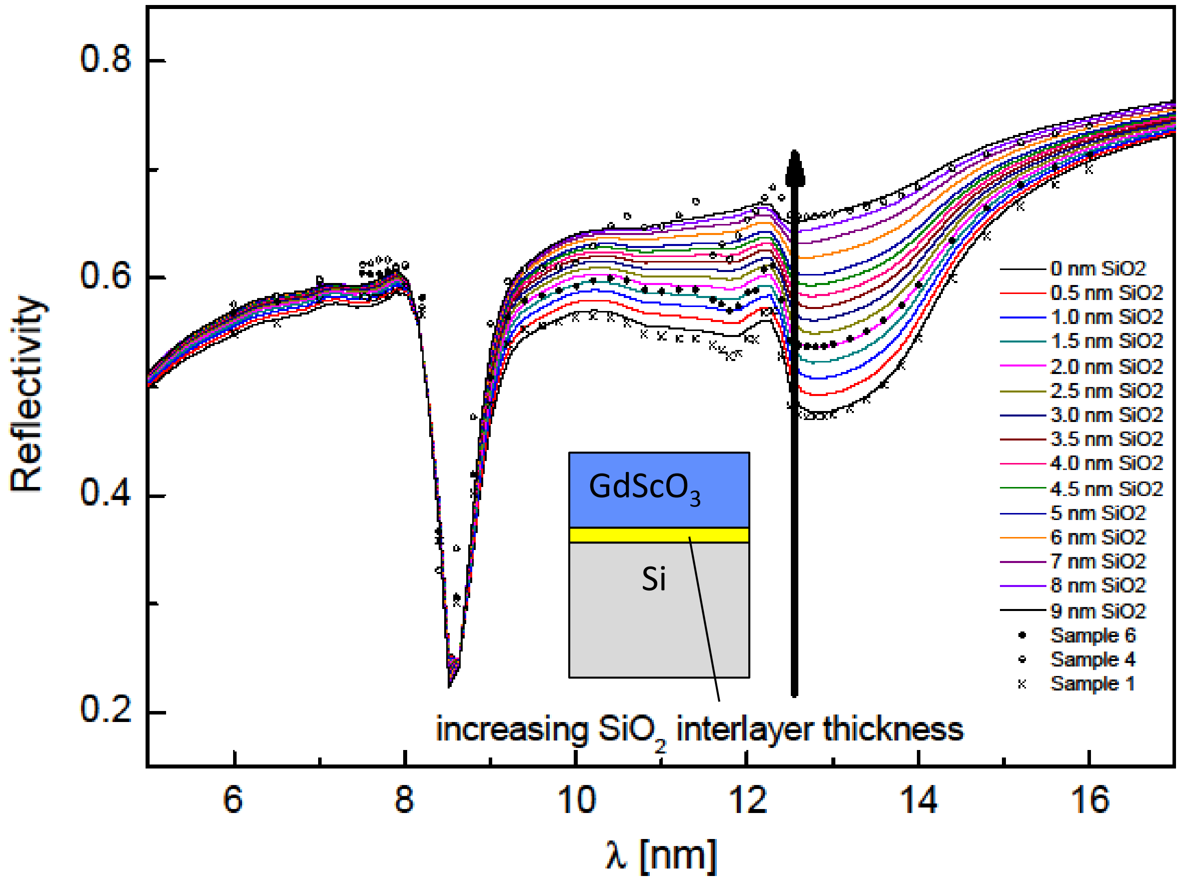
Interfacial layer thickness determination in gate stacks

$GdScO_3$ gate stack with differing „parasitic“ oxide thickness



- high contrast for buried ultra-thin interlayer (thickness high-k: 5 nm)
- difficult to access with other all-optical (non-destructive) methods
- characteristic NEXAFS fingerprint at Si L-edge (12.4 nm) visible
- database built-up needed („fingerprint-concept“)

Proof-of-Principle investigations carried out at PTB, BESSY II and in collaboration with J. Schubert (FZJ IBN-1)

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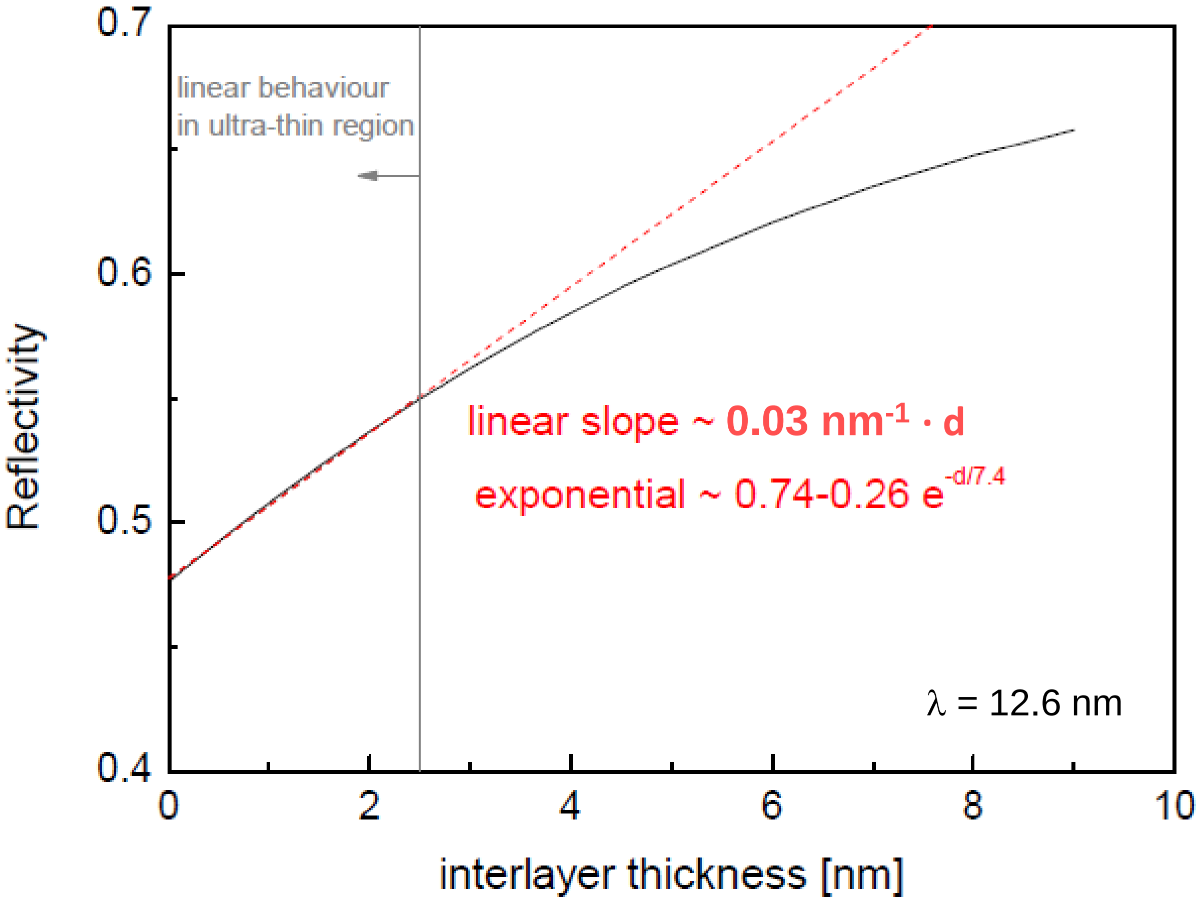

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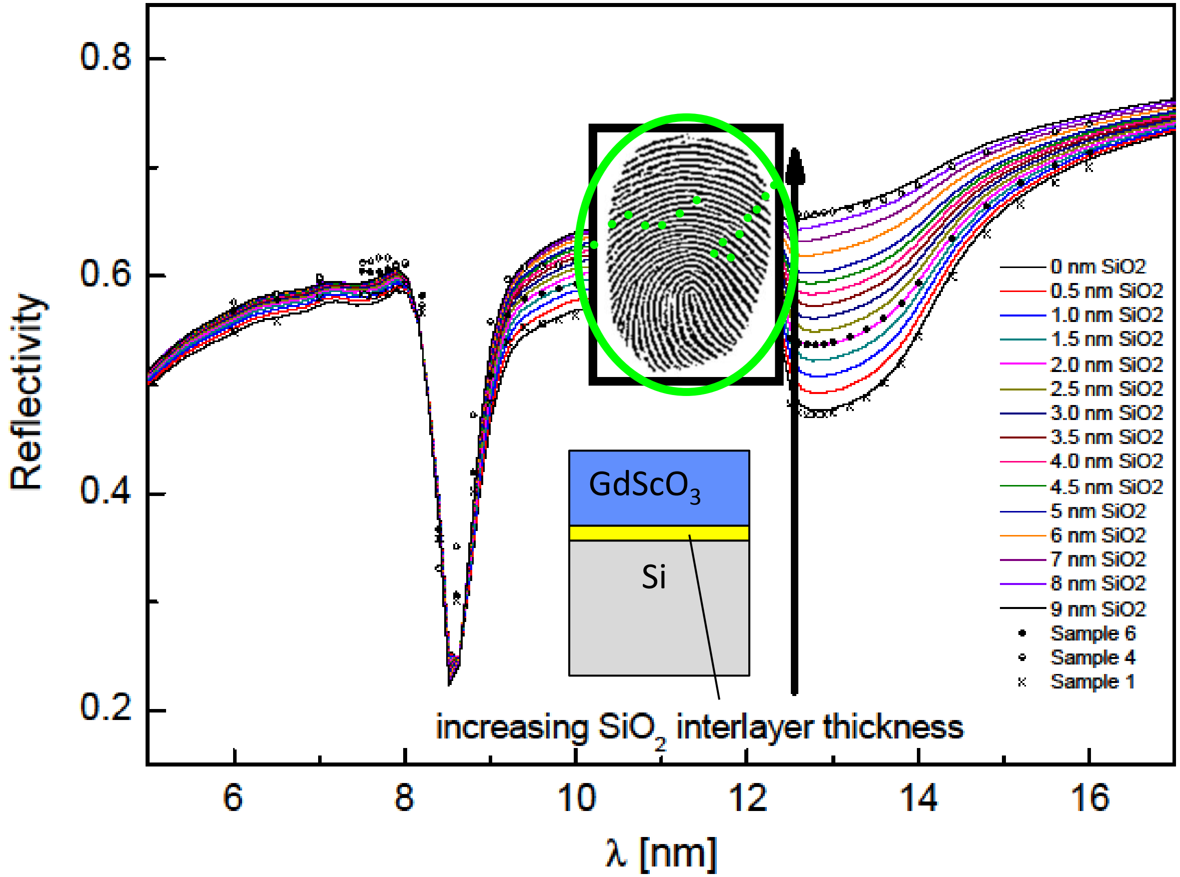

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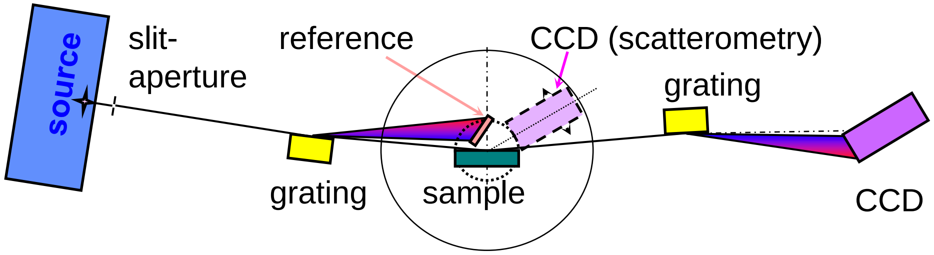
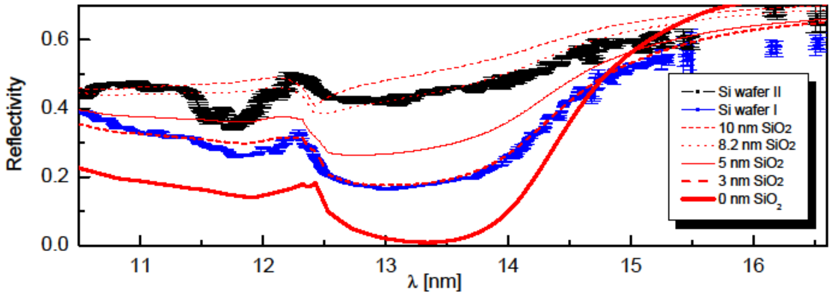
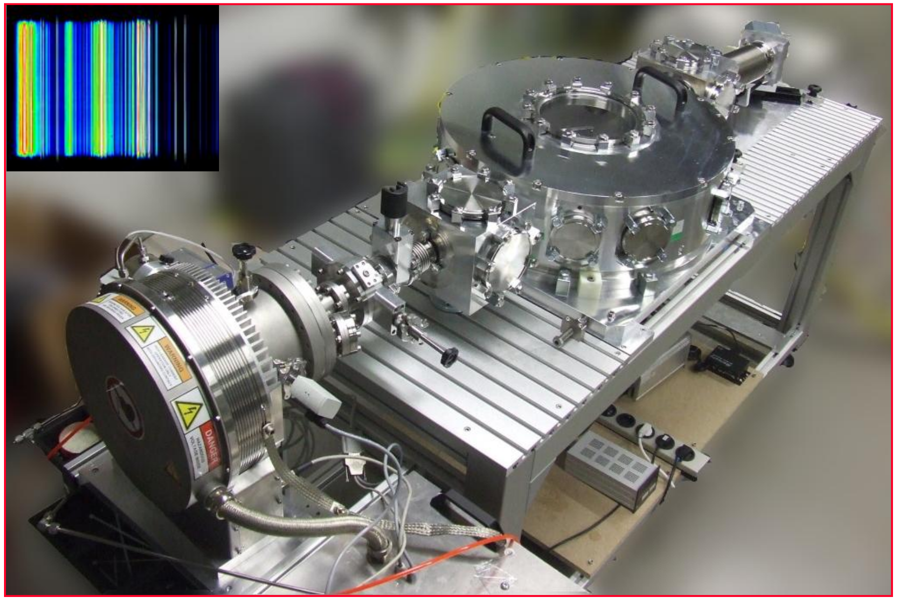
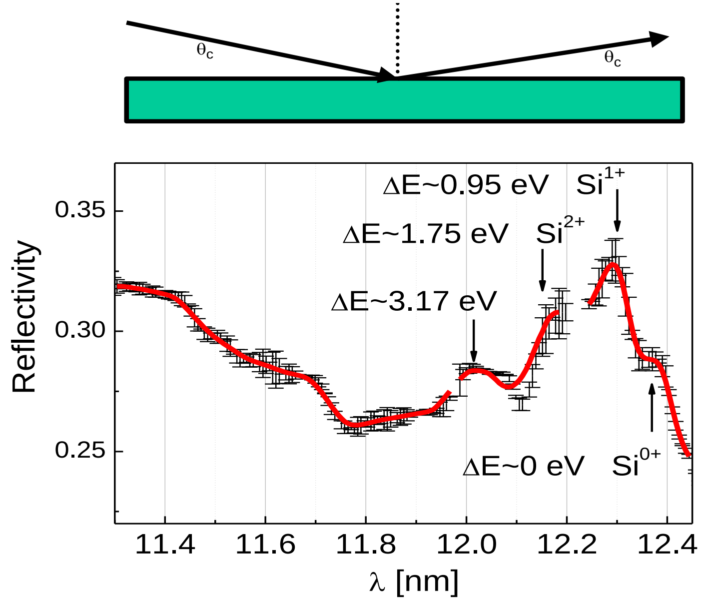
Grazing incidence reflectometer - system design









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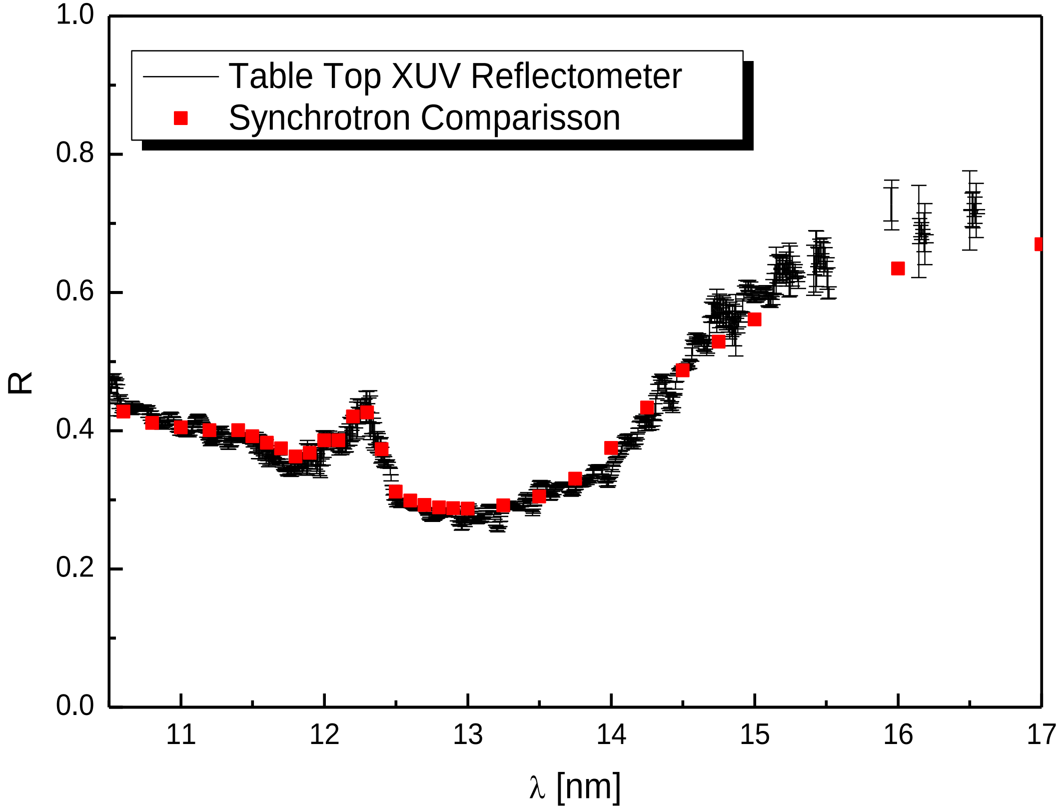
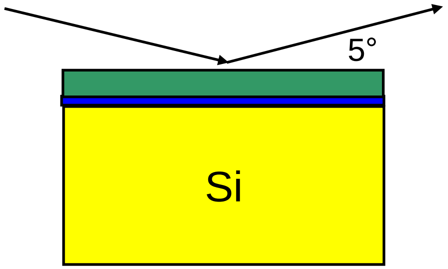
Examples: Burried Ultra-Thin Oxide Layers

Determination of ultra thin HfO_2 layers and burried oxide





Layer Model:

Hf_3N_4 d: 0.51 nm, density: 12.2 g/cm^3
HfO_2 d: 0.97 nm, density: 9.4 g/cm^3
SiO_2 d: 1.00 nm, density: 2.4 g/cm^3
Si_3N_4 d: 0.83 nm, density: 4.1 g/cm^3
Si substrate
interlayer roughness/diffusion: 0.33 nm

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Cross-characterization of a HfO_2 gate dielectric stack

	MEIS	ARXPS	GIXUVR
In	Ion	Photon	Photon
Out	Ion	Electron	Photon
Typ. Depth of Analysis	1 µm	1-10 nm	1-100 nm
Typ. Spatial Resolution	1 mm	> 50 µm	µm-mm
Typ. Measuring Time	Min-hours	hours	ms-s
Required Vacuum Level	10^{-6}-10^{-9} mbar	10^{-6}-10^{-9} mbar	10^{-2}- 10^{-5} mbar
Determined Layer model	(5Å)HfO_2/(3Å)$HfO_2N_{1.5}$/ (3Å)$HfSi_{2.4}O_4N$/(9Å)$HfSi_2O_4$/ (3Å)SiO_2/Si	(5Å)Hf_3N_4/(9.6Å)HfO_2/ (10.4Å)SiO_2/(7.9 Å)Si_3N_4/Si {(3Å)HfO_2/(5Å)HfON/(7Å)HfO_2/(7Å)SiO_2/(6Å)SiON/Si}	(5.1Å)Hf_3N_4/(9.7Å)HfO_2/ (10.0Å)SiO_2/(8.3Å)Si_3N_4/Si
Strength for high-k analysis	Even slight residuals / dopants / contaminants noticeable and identifiable (pure elements)	Detailed depth profile including the interfaces visualizing diffuseness of e.g. nitride into the stack	density sensitive, fast measuring times, NEXAFS fingerprint of interface
Weakness for high-k analysis	partly destructive for the surface due to ion bombardment, model dependent layer parameters	very long measuring times, limited depth of analysis if significant layers are buried even deeper, model dependent layer parameters	Layer parameters are model dependent, limited NEXAFS database

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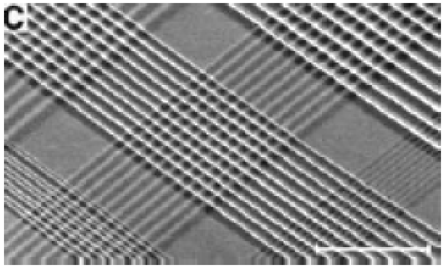
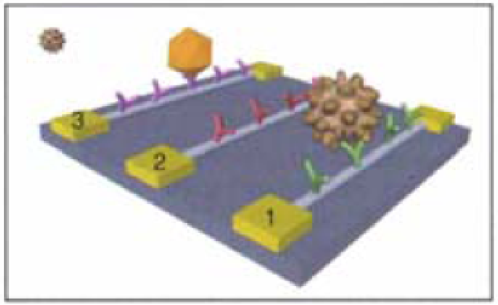
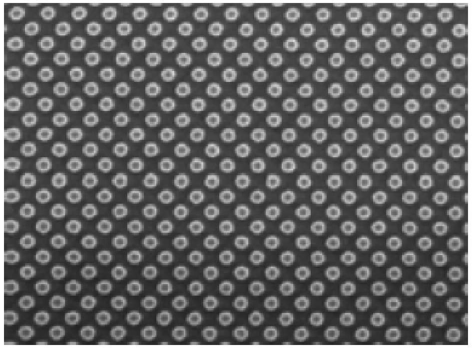
Nano-structuring - Motivation



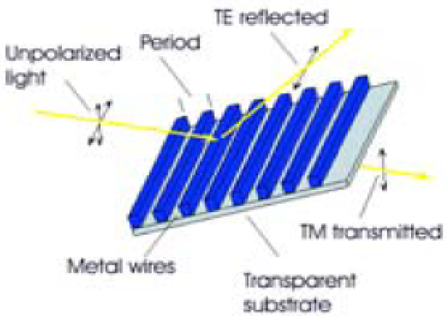
Nanowire cross-bar circuit
N. Melosh, Science, 2003.



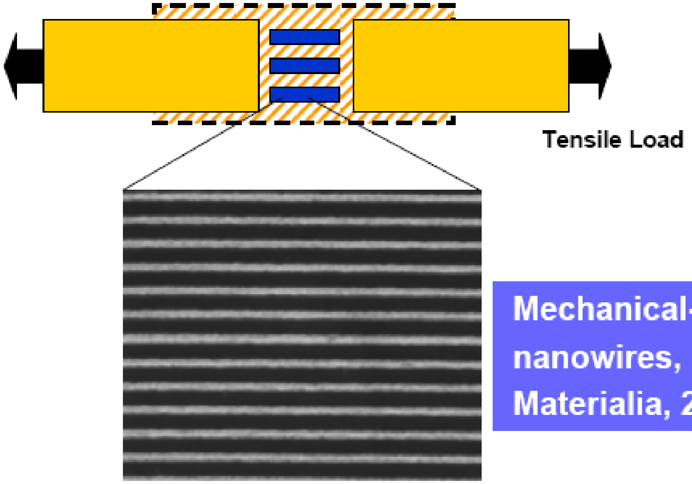
Nanowire sensor array
G. Zheng, Nature Biotechnology, 2005.



Patterned magnetic media

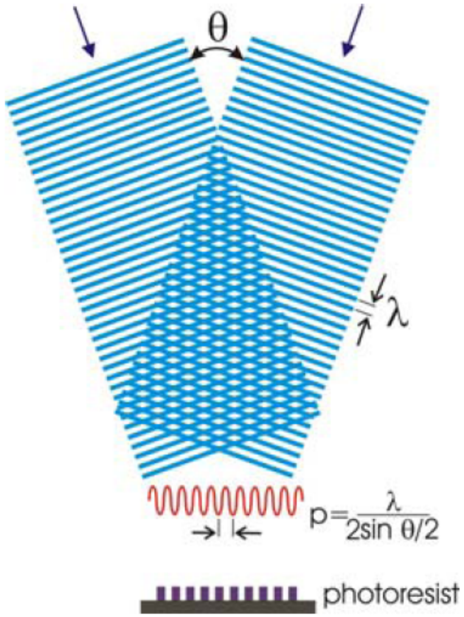


Sub-wavelength wire-grid polarizer

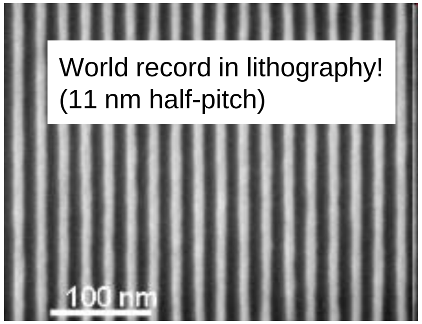


Mechanical-properties of nanowires, S. Olliges, Acta Materialia, 2007.

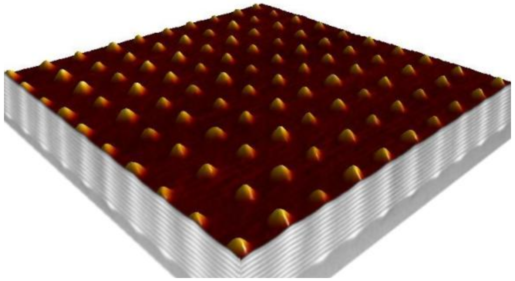
EUV interference lithography



- **Large-area periodic structures**
- **Large depth of focus**
- **Requires coherent light**
- **Low cost – no complicated and expensive optics**
- **Ultimate resolution for the wavelength (~λ/4)**
  EUV: λ = 11 nm –> feature size ~ 3 nm!
- **no charging effect, negligible proximity effect**
- **moderate throughput**



Auzelyte *et al*, J. Micro/Nanolith. MEMS MOEMS 8(2), 021204 (2009)



3D Si/Ge QD crystals

Grützmacher *et al*, NANO LETTERS 7, 3150 (2007)

- **Successfully used with synchrotron radiation**
- **Enabling technology, if achieved with laboratory sources**

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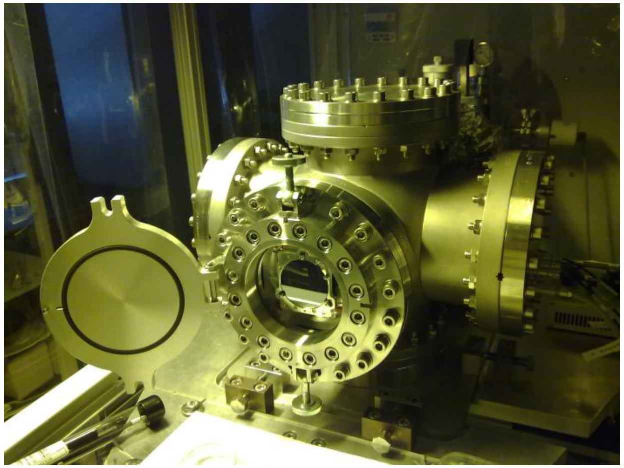
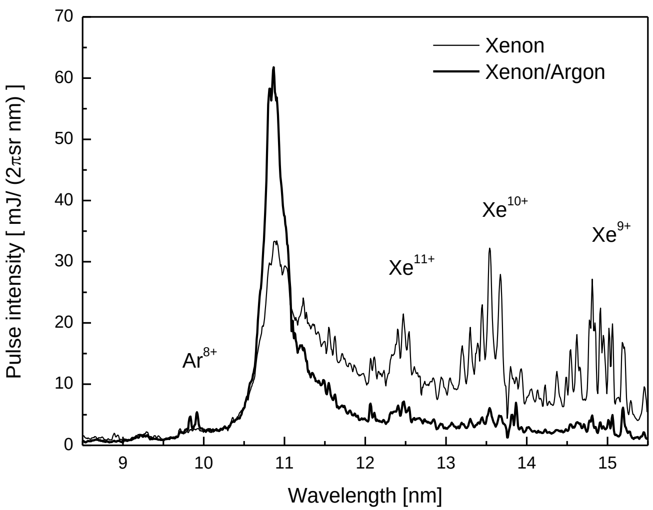
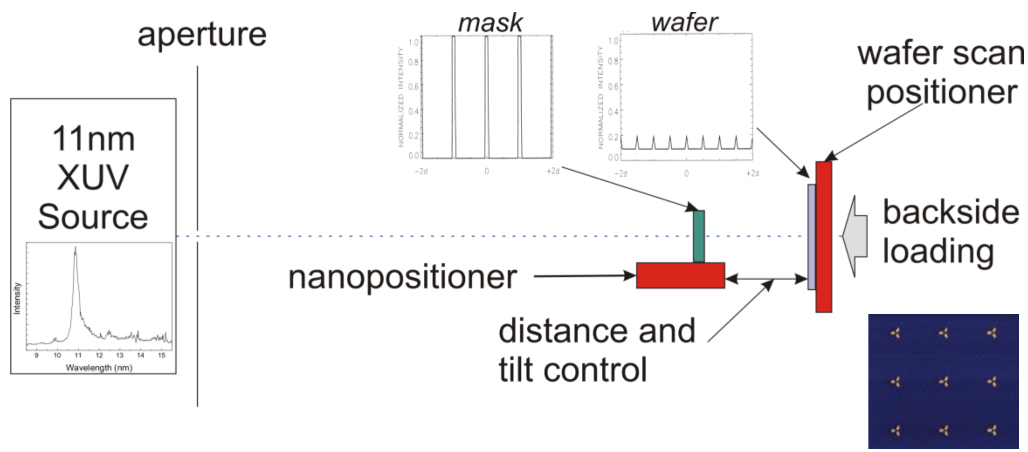
EUV Interference patterning with a laboratory EUV source



- Proof-of-principle setup with gas discharge plasma source
- Twofold reduction of structure size and period from mask onto wafer due to achromatic Talbot self-imaging
- Exposure fields of ~ 100 x 100 µm² on 2” wafers
- New efficient mask technology for λ = 11 nm developed
- Spectral output optimized for power and bandwidth at 11 nm
- Spatial coherence lengths up to 27 µm was measured





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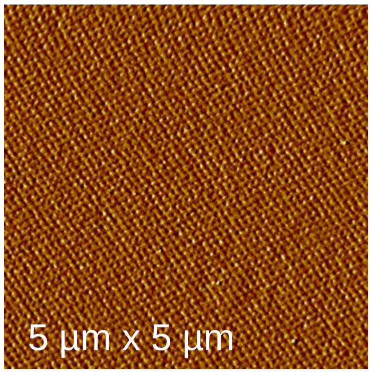
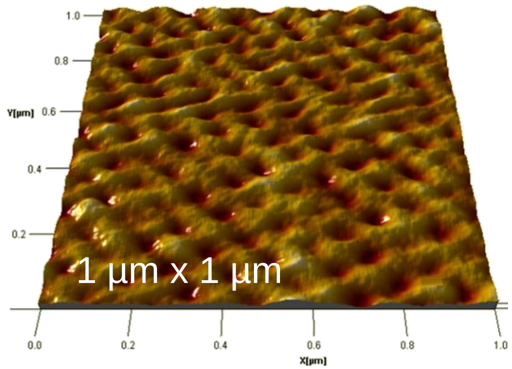
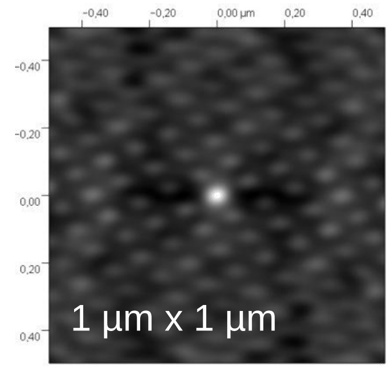
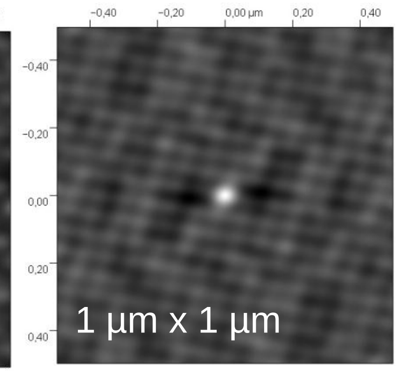
Experimental results





z<0.1µm





z=0.91µm, p=100nm

First monochromatic Talbot distance

z=58.5µm, p=72nm

Achromatic Talbot regime

AFM measurements of PMMA resist structured with Nb/Ni pinhole mask in the contact mode.

- Period of structures - 100 nm
- Hole diameter – 40 nm
- Array size - 265 x 265 µm

2D autocorrelation function of AFM measurements of exposed PMMA resist

Period is reduced by factor $\sqrt{2}$

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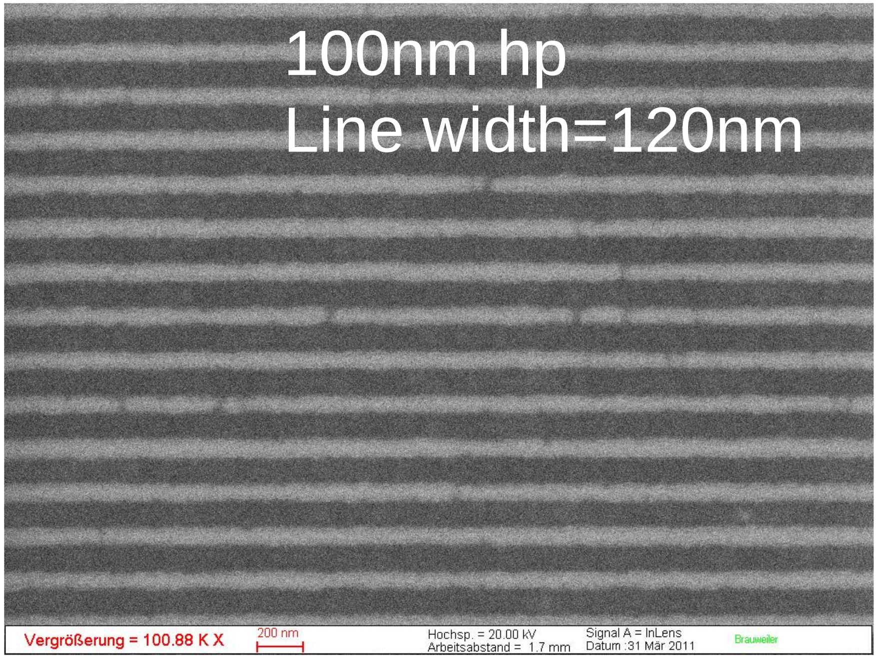
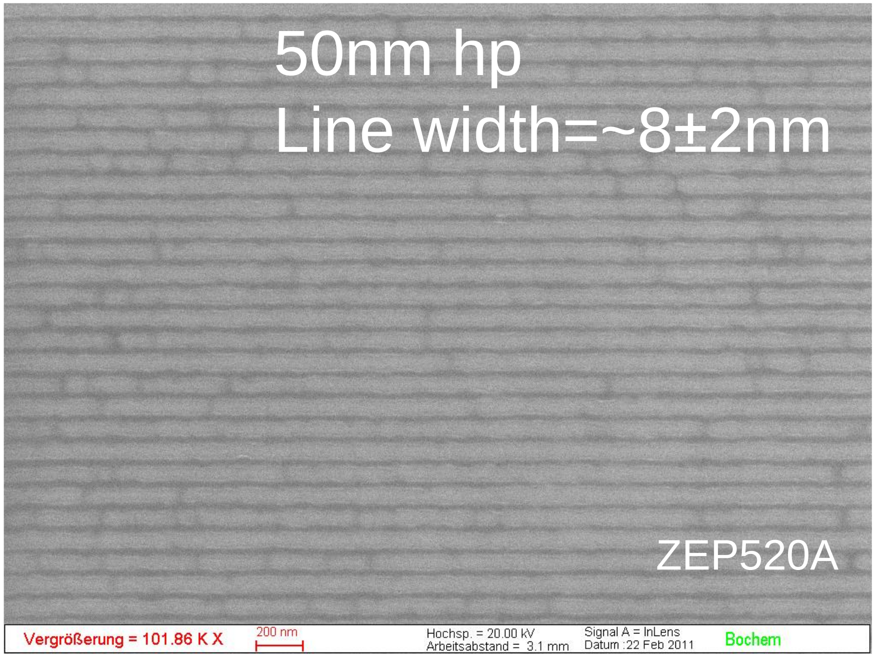
Experimental results



Distance to mask z few µm

Proximity printing



Distance to mask z= 50 µm

achromatic Talbot (with the same transmission mask!)

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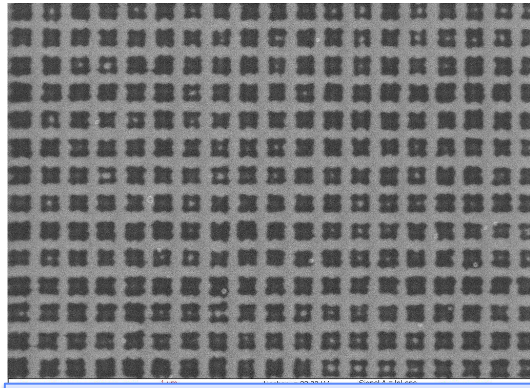
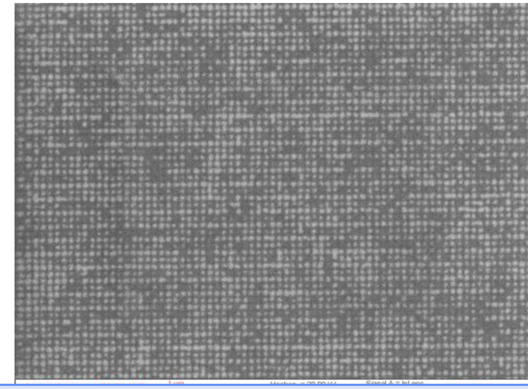
Applications

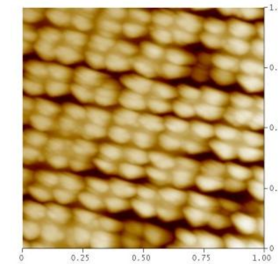


SFB 917
Nanoswitches

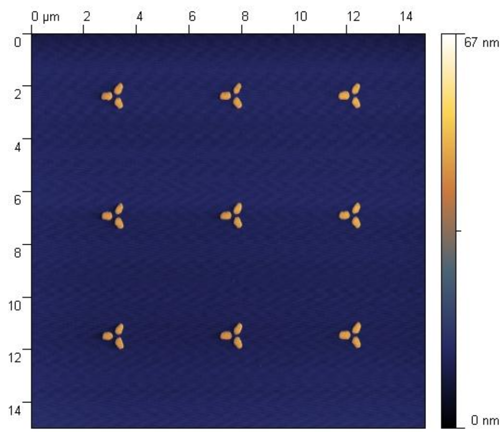
cross-bar arrays for PCRAM

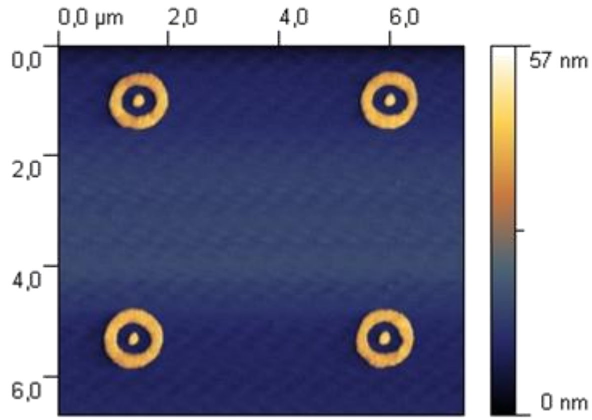


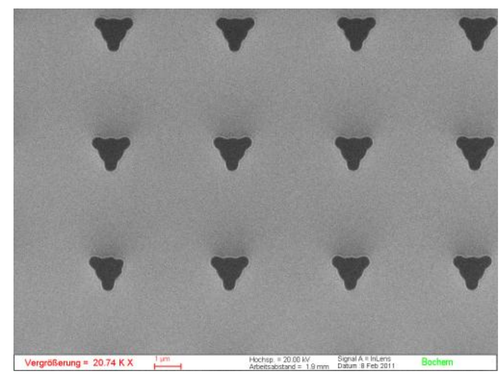
JÜLICH
FORSCHUNGSZENTRUM



nanodot-arrays for QD self assembly

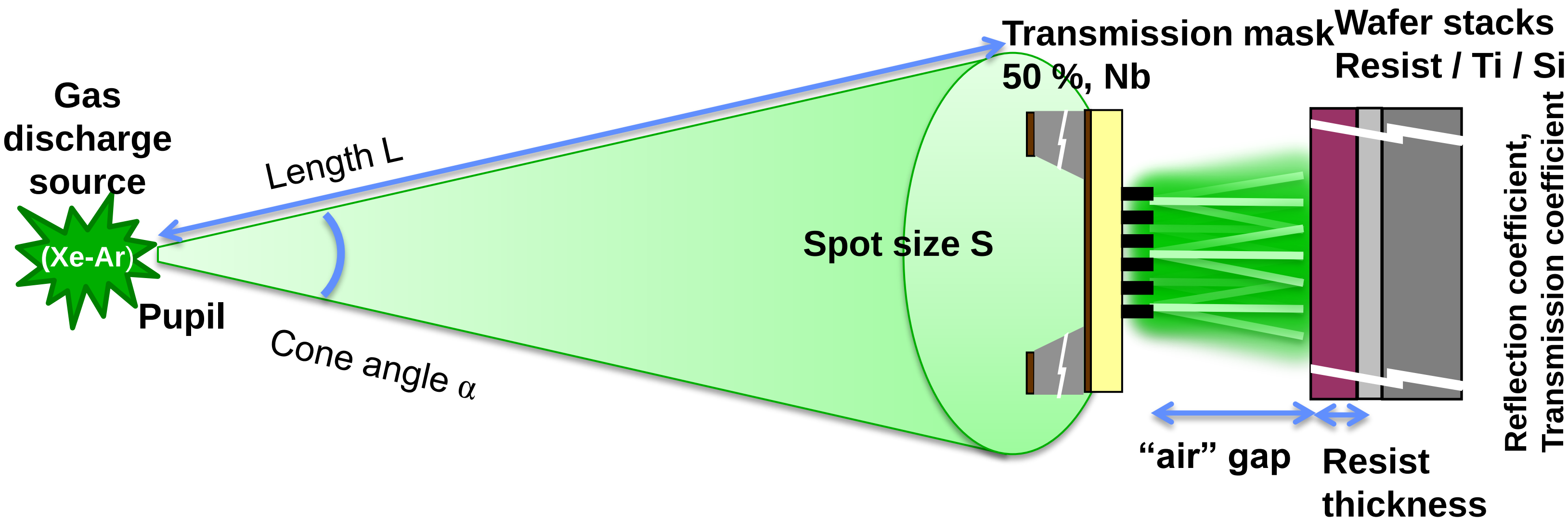






Nanophotonic resonators

Lithography simulations (Dr. Litho)

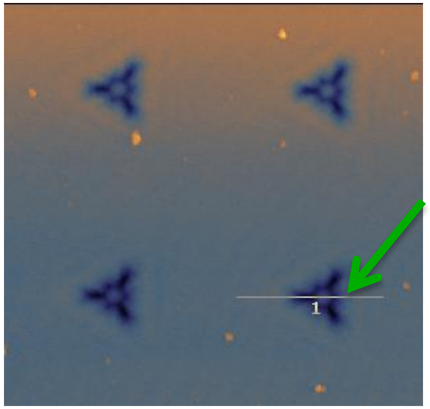


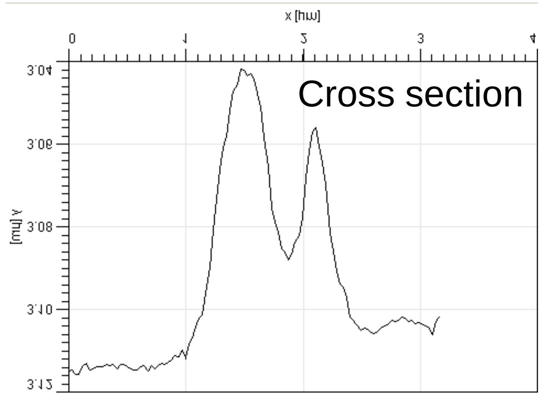
❖ Simulation modules (→ Research area)

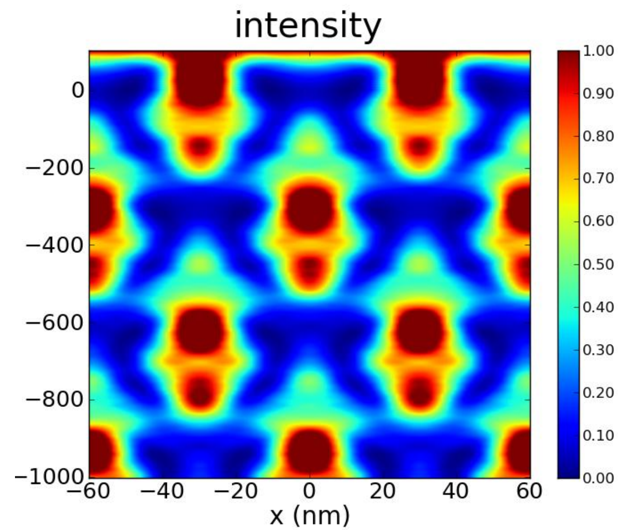
Source	Mask	Resist
✓ Wavelength ✓ Bandwidth ✓ Pupil shape ✓ Cone angle ✓ Polarization	✓ Absorber ✓ Transmittance ✓ Scalar diffraction models (Kirchhoff, RS I, II) ✓ Rigorous diffraction simulation	✓ Stack, Resist parameter (Dill ABC) ✓ Exposure time ✓ PEB time, temp. (Diffusion) ✓ Develop time (Mack parameter) ✓ Resist profile (Process windows)

Comparison of experiment and simulations

- **Experiment** (1 min, 15µm gap, PMMA)

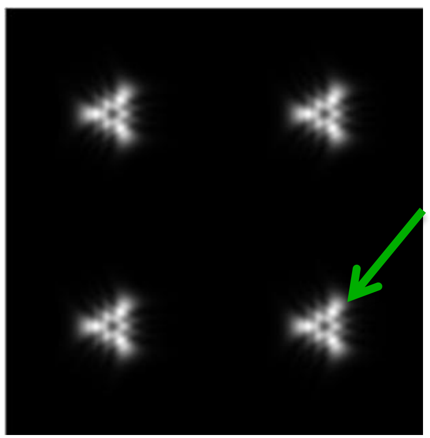


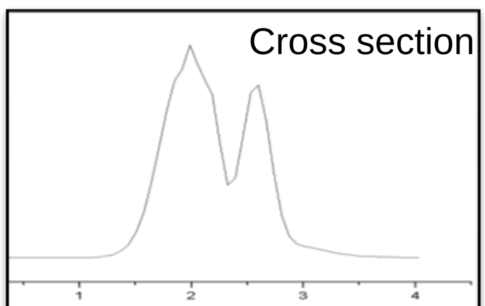




30 nm hp Talbot carpet

- **Simulation** (Aerial image at 15 µm gap)





✓ **Simulations show good correlation with experimental results**

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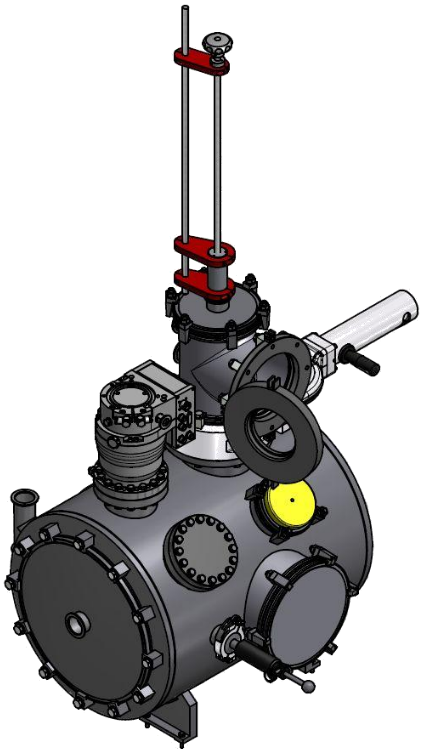
EUV-IL exposure tool for 4“ wafers



- Input power 5.6kW
- Pinch radius 100µm
- 100W/(mm^{2}sr) brilliance at 10.9 nm
- 65mm x 65mm exposable
- Single field size > 4mm^2
- Field exposure time < 30s @ 30 mJ/cm^2

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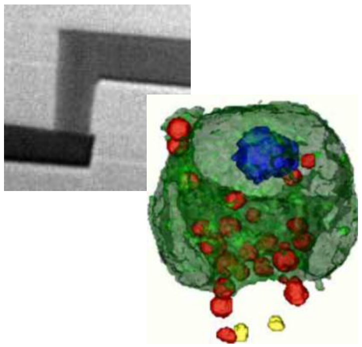
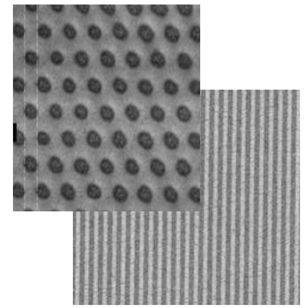
Applications summary

XUV: short wavelength and strong light matter interaction → lateral & in-depth (3d) nm resolutions with element sensitivity and high throughput



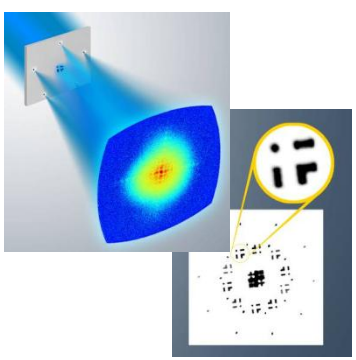
Microscopy

- 3d imaging (cells, electronics)
- “no” sample preparation
- several µm penetration depths
- magnetic (spin) contrast with polarized light



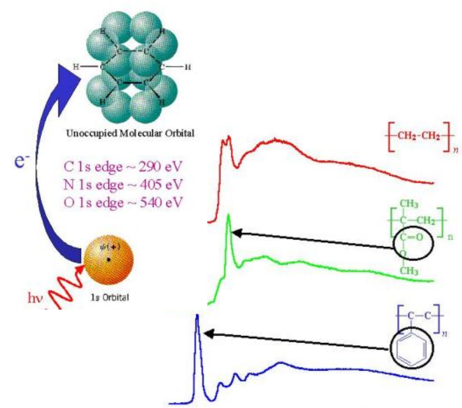
Patterning

- high density arrays
- large exposition areas
- access to < 10 nm scale
- negligible proximity effect
- independent on substrate



Scatter/diffractometry

- nano-roughness
- nano-structures arrays
- nano-defect inspection
- lens less imaging with coherent light



Spectroscopies

- element selectivity
- chemical bonding (NEXAFS)
- small penetration depths of radiation (<100 nm)
- large grazing incidence angle

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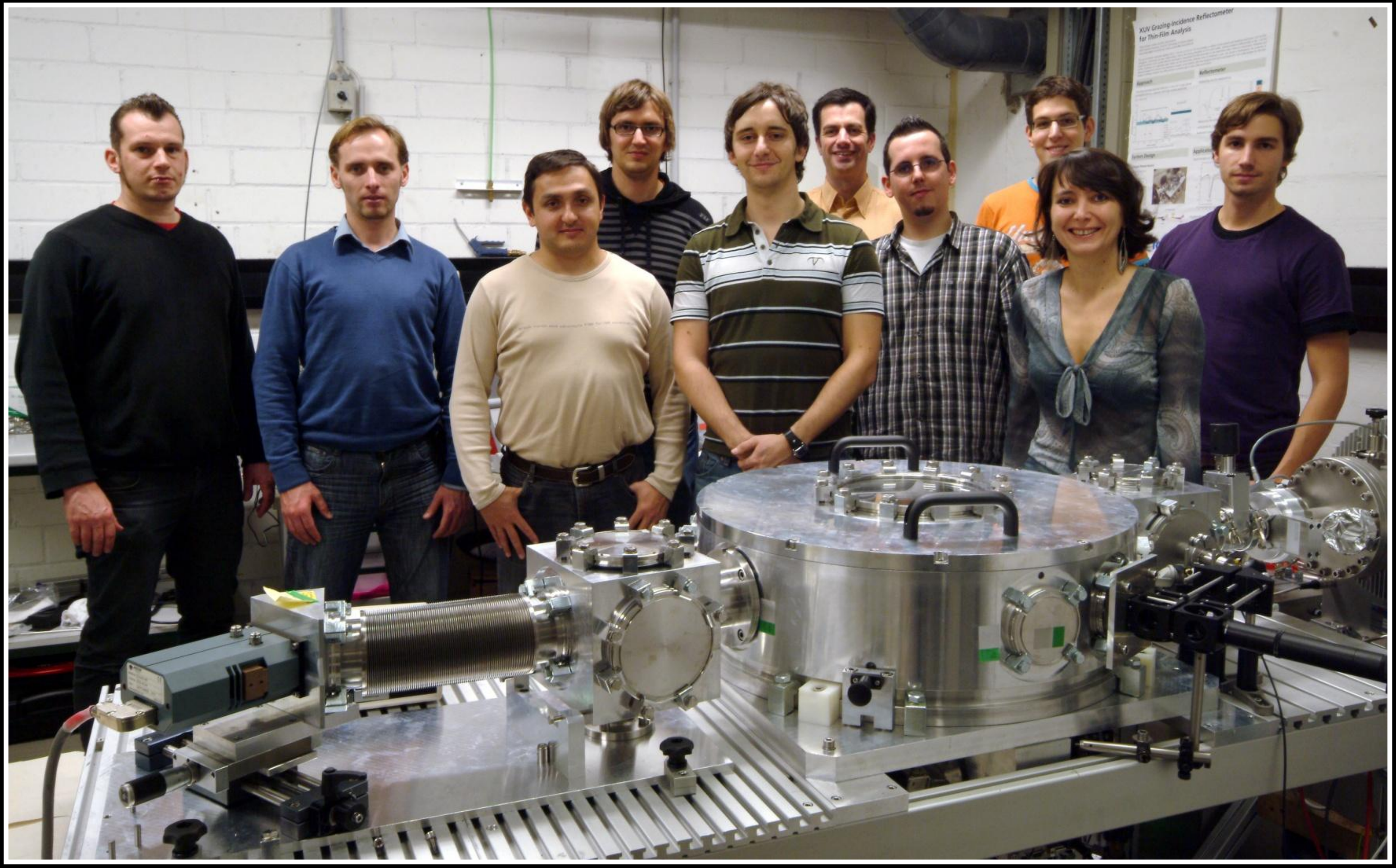
Wolfgang Diete, Azadeh Farahzadi, Bernhard Jaegle, Rainer Lebert, Urs Wiesemann, …

JARA Jülich Aachen Research Alliance

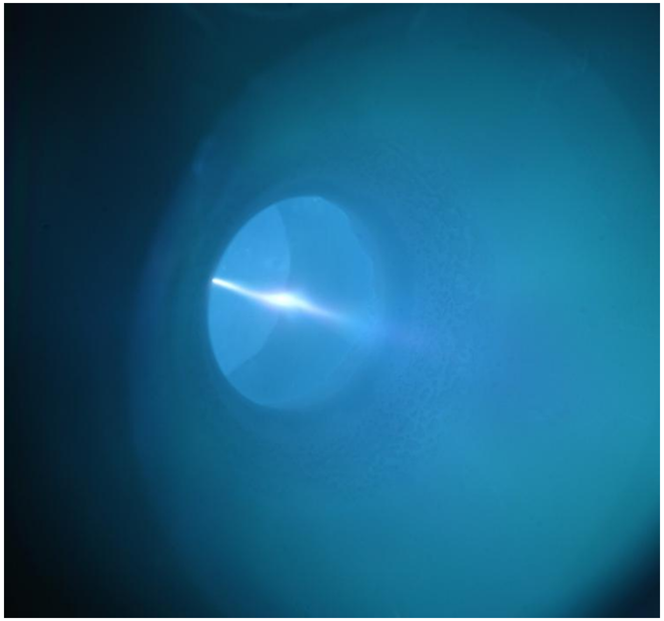
Thank you very much for your attention!



Questions? Comments?

Overview

- XUV radiation and its interaction with matter
  - Atomic scattering factors
  - Index of refraction
  - Applications summary
- Laboratory plasma based XUV sources
  - Etendue characteristics
- Exemplary laboratory applications
  - EUV- and XUV-microscopy
  - XUV spectroscopic reflectometry
  - Nanostructuring
- Outlook



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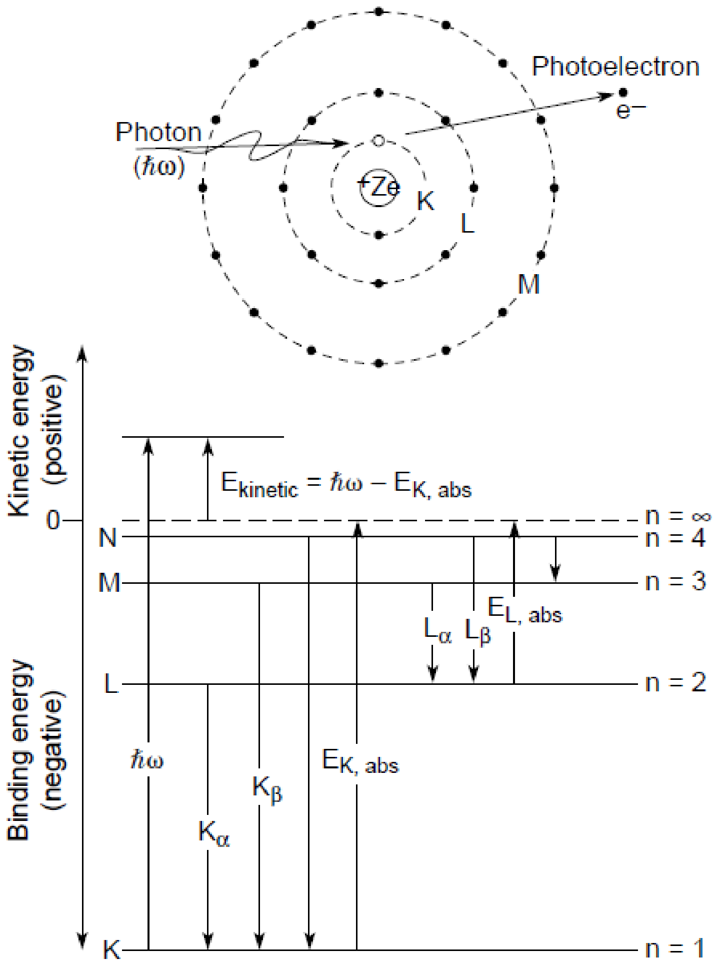
Binding energies



Element	K1s	L_12s	$L_22p_{1/2}$	$L_32p_{3/2}$	M_13s	$M_23p_{1/2}$	$M_33p_{3/2}$	$M_43d_{3/2}$	$M_53d_{5/2}$	N_14s
1 H	13.6									
2 He	24.6									
6 C	284.2									
7 N	409.9	37.3								
8 O	543.1	41.6								
13 Al	1559.6	117.8	72.9	72.5						
14 Si	1838.9	149.7	99.8	99.2						
16 S	2472	230.9	163.6	162.5						
20 Ca	4038.5	438.4	349.7	346.2	44.3	25.4	25.4			
22 Ti	4966.4	560.9	461.2	453.8	58.7	32.6	32.6			
24 Cr	5989.2	695.7	583.8	574.1	74.1	42.2	42.2			
26 Fe	7112.0	844.6	719.9	706.8	91.3	52.7	52.7			
27 Co	7708.9	925.1	793.3	778.1	101.0	58.9	58.9			
28 Ni	8332.8	1008.6	870.0	852.7	110.8	68.0	66.2			
29 Cu	8978.9	1096.7	952.3	932.5	122.5	77.3	75.1			
30 Zn	9658.6	1196.2	1044.9	1021.8	139.8	91.4	88.6	10.2	10.1	
42 Mo	19999.5	2865.5	2625.1	2520.2	506.3	411.6	394.0	231.1	227.9	63.2
47 Ag	25514.0	3805.8	3523.7	3351.1	719.0	603.8	573.0	374.0	368.0	97.0
54 Xe	34561.4	5452.8	5103.7	4782.2	1148.7	1002.1	940.6	689.0	676.4	213.2
79 Au	80724.9	14352.8	13733.6	11918.7	3424.9	3147.8	2743.0	2291.1	2205.7	762.1

EUV, λ ~ 5 – 50 nm

SXR, λ ~ 1 – 5 nm

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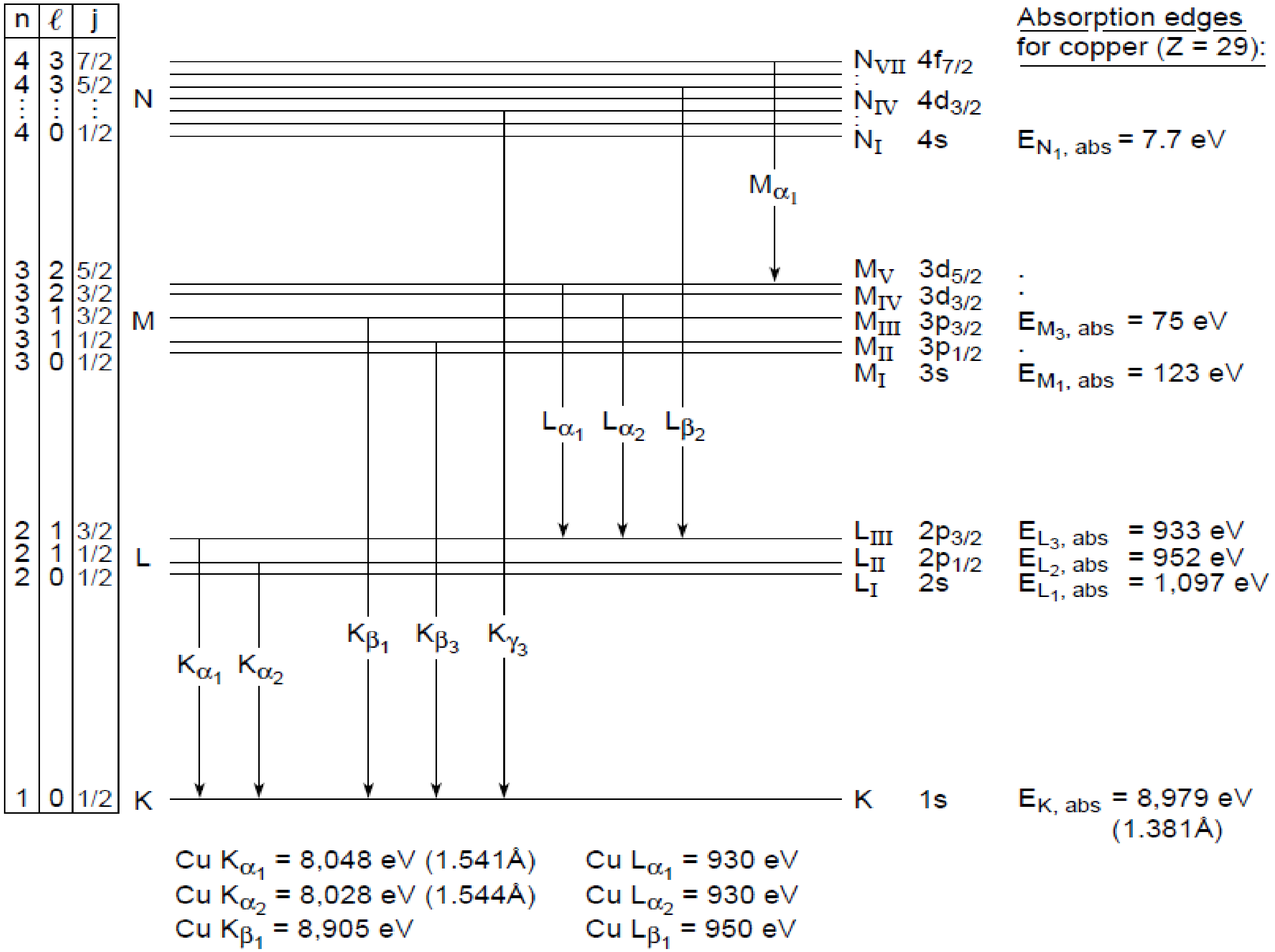
Energy levels, quantum numbers, and allowed transitions for the copper atom



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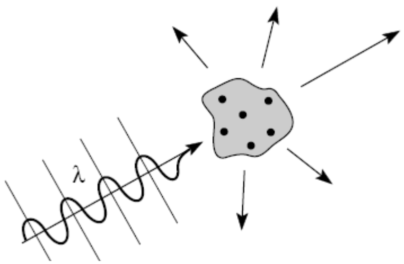
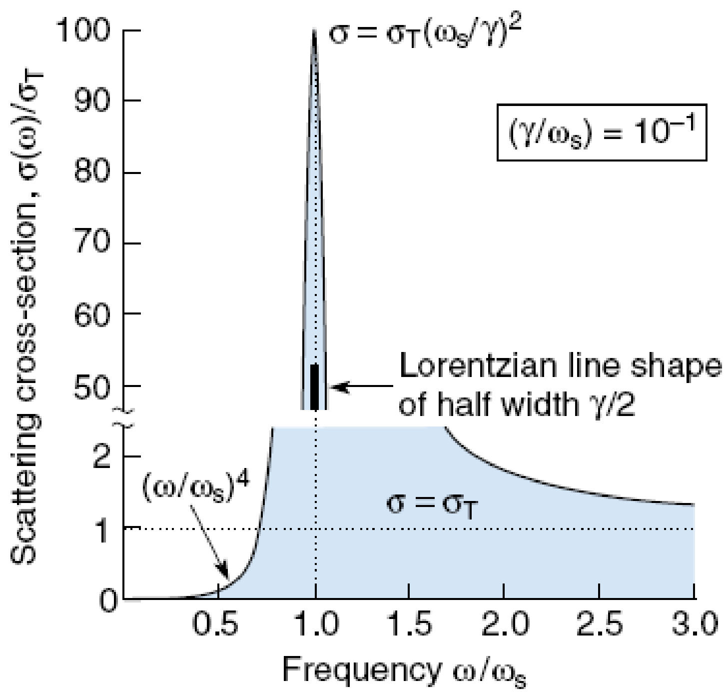
Description of light-matter interaction – scattering cross sections



$$\sigma \equiv \frac{\bar{P}_{\text{scattered}}}{|\bar{S}|}$$



Scattering by a free electron (Thomson):

$$\sigma_T = \frac{8\pi}{3} \cdot r_e^2$$

Scattering by bound electrons:

$$\sigma = \frac{8\pi}{3} \cdot r_e^2 \cdot \frac{\omega^4}{\left(\omega^2 - \omega_s^2\right)^2 + (\gamma\omega)^2}$$

Rayleigh scattering $(\omega^2 << \omega_s^2$ **and** $\gamma << \omega_S)$

$$\sigma = \frac{8\pi}{3} \cdot r_e^2 \cdot \left(\frac{\omega}{\omega_s}\right)^4 = \frac{8\pi}{3} \cdot r_e^2 \cdot \left(\frac{\lambda_s}{\lambda}\right)^4$$

Scattering by a multi-electron atom:

$$\sigma = \frac{8\pi}{3} \cdot |f|^2 \cdot r_e^2 \ \textbf{with}\ f(\Delta\mathbf{k}, \omega) = \sum_{S=1}^{Z} \frac{\omega^2 \cdot e^{-i\Delta\mathbf{k}\cdot\Delta r}}{\left(\omega^2 - \omega_s^2 + i\gamma\omega\right)}$$

atomic scattering factor

$$f^0(\omega) = \sum_{s=1}^{Z} \frac{\omega^2}{\omega^2 - \omega_s^2 + i\gamma\omega} = f_1^0(\omega) - i f_2^0(\omega)$$

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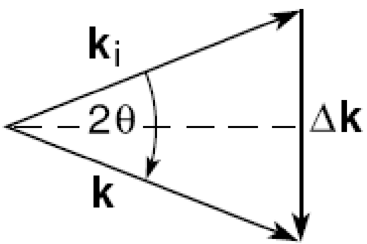
Complex atomic scattering factor – What is different to x-ray?

$$E(\mathbf{r},t) = -\frac{r_e}{r}\underbrace{\left[\sum_{s=1}^{Z}\frac{\omega^2 e^{-i\Delta\mathbf{k}\cdot\Delta\mathbf{r}_s}}{\omega^2-\omega_s^2+i\gamma\omega}\right]}_{f(\Delta\mathbf{k},\,\omega)} E_i \sin\Theta\, e^{-i\omega(t-r/c)}$$



$$\Delta\mathbf{k} = \mathbf{k} - \mathbf{k}_i$$

$$|\Delta\mathbf{k}| = 2k_i \sin\theta$$

$|\Delta\mathbf{k}\cdot\Delta\mathbf{r}_s| \rightarrow 0$ for $a_0/\lambda \ll 1$ (long wavelength limit)

$|\Delta\mathbf{k}\cdot\Delta\mathbf{r}_s| \rightarrow 0$ for $\theta \ll 1$ (forward scattering)

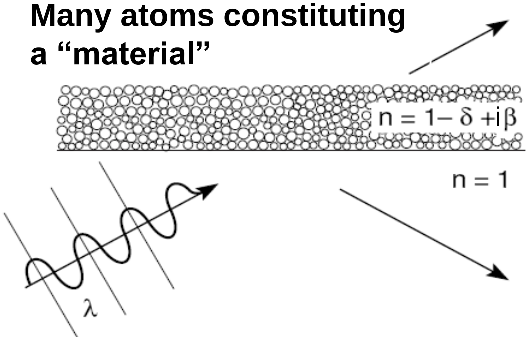
=> $$f^0(\omega) = \sum_{s=1}^{Z}\frac{\omega^2}{\omega^2-\omega_s^2+i\gamma\omega} = f_1^0(\omega) - i f_2^0(\omega)$$

Refractive index

$$n(\omega) = 1 - \frac{n_a r_e \lambda^2}{2\pi}\left(f_1^0 - i f_2^0\right) = 1 - \delta + i\beta$$

$$\mathbf{E}(\mathbf{r},t) = \underbrace{\mathbf{E}_0 e^{-i\omega(t-r/c)}}_{\text{vacuum propagation}}\ \underbrace{e^{-i(2\pi\delta/\lambda)r}}_{\phi\text{-shift}}\ \underbrace{e^{-(2\pi\beta/\lambda)r}}_{\text{decay}}$$

Many atoms constituting a “material”



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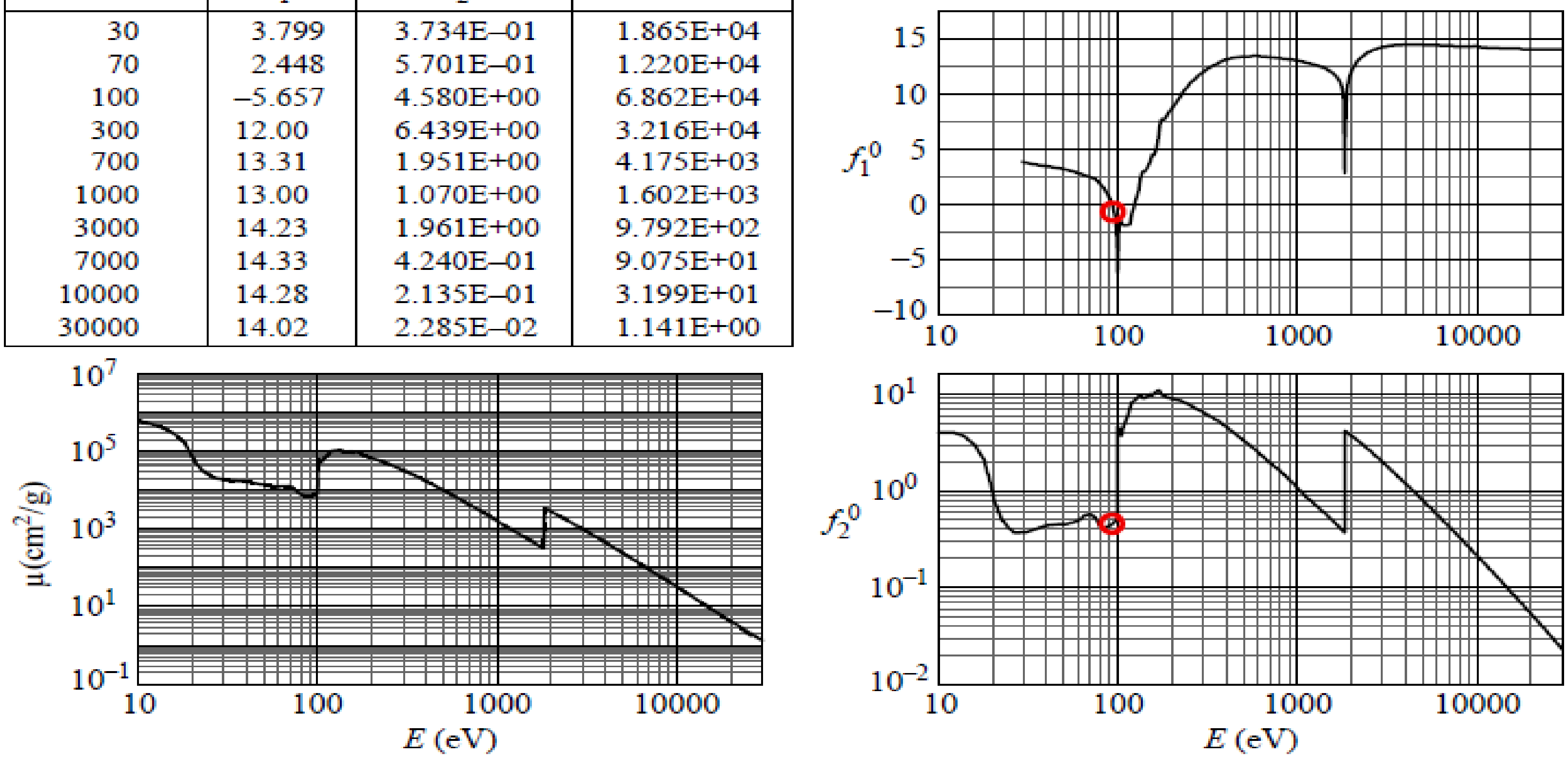
Example: atomic scattering factors for silicon (Z = 14)

σ_a(barns/atom) = μ(cm^2/g) × 46.64
E(keV)μ(cm^2/g) = f_2^0 × 1498.22

Silicon (Si)
Z = 14
Atomic weight = 28.086

Energy (eV)	f_1^0	f_2^0	μ(cm^2/g)
30	3.799	3.734E–01	1.865E+04
70	2.448	5.701E–01	1.220E+04
100	–5.657	4.580E+00	6.862E+04
300	12.00	6.439E+00	3.216E+04
700	13.31	1.951E+00	4.175E+03
1000	13.00	1.070E+00	1.602E+03
3000	14.23	1.961E+00	9.792E+02
7000	14.33	4.240E–01	9.075E+01
10000	14.28	2.135E–01	3.199E+01
30000	14.02	2.285E–02	1.141E+00



Edge Energies:	K	1838.9 eV	L_1	149.7 eV
			L_2	99.8 eV
			L_3	99.2 eV

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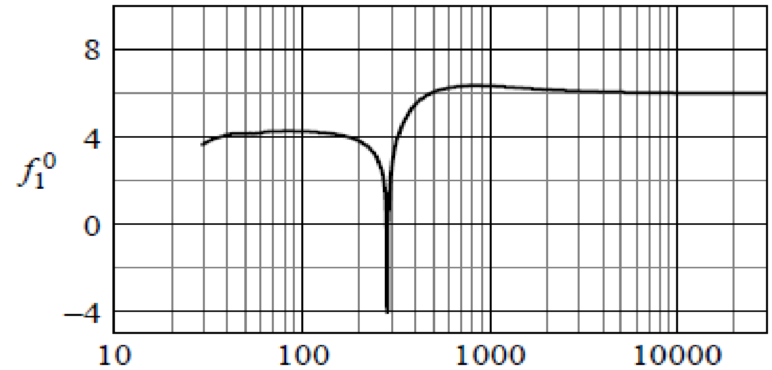
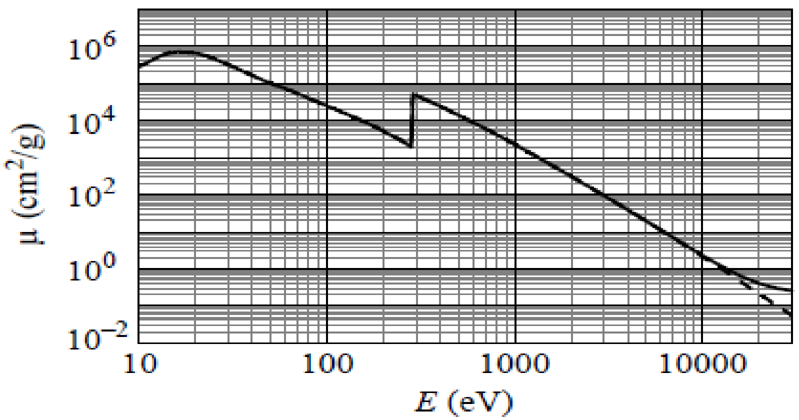
Atomic scattering factors for carbon (Z = 6)

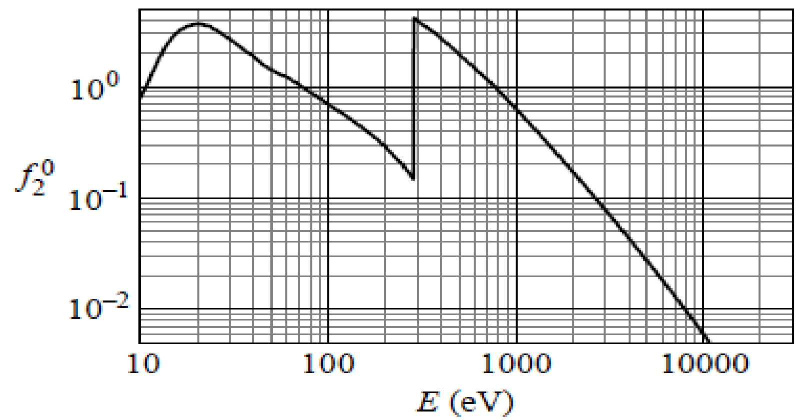
$\sigma_a(\text{barns/atom}) = \mu(\text{cm}^2/\text{g}) \times 19.95$
$E(\text{keV})\mu(\text{cm}^2/\text{g}) = f_2^0 \times 3503.31$

Carbon (C)
Z = 6
Atomic weight = 12.011

Energy (eV)	f_1^0	f_2^0	μ (cm^2/g)
30	3.692	2.664E+00	3.111E+05
70	4.249	1.039E+00	5.201E+04
100	4.253	6.960E-01	2.438E+04
300	2.703	3.923E+00	4.581E+04
700	6.316	1.174E+00	5.878E+03
1000	6.332	6.328E–01	2.217E+03
3000	6.097	7.745E–02	9.044E+01
7000	6.025	1.306E–02	6.536E+00
10000	6.013	5.892E–03	2.064E+00
30000	6.000	4.425E–04	5.168E–02







Edge Energies: K 284.2 eV

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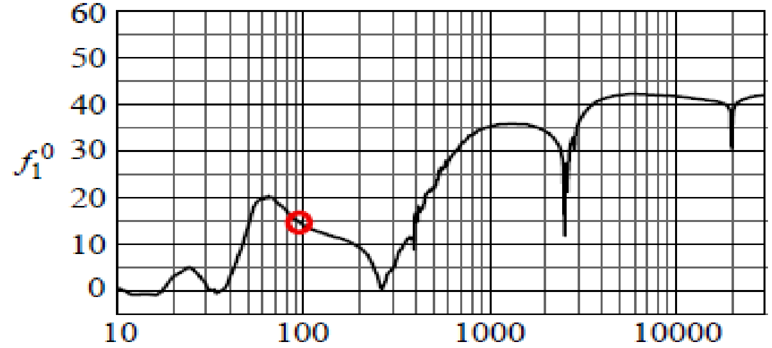
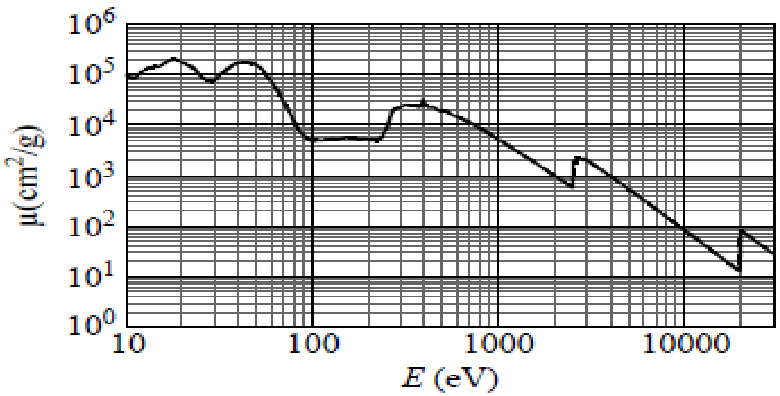
Atomic scattering factors for molybdenum (Z = 42)

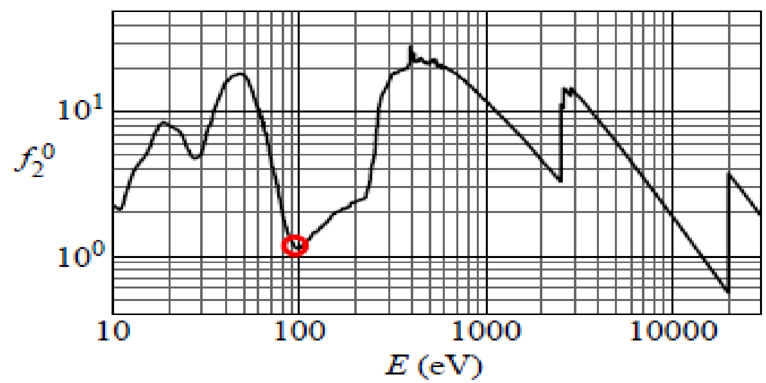
σ_a(barns/atom) = μ(cm^2/g) × 159.31
E(keV)μ(cm^2/g) = f_2^0 × 438.59

Molybdenum (Mo)
Z = 42
Atomic weight = 95.940

Energy (eV)	f_1^0	f_2^0	μ(cm^2/g)
30	1.071	5.292E+00	7.736E+04
70	19.38	4.732E+00	2.965E+04
100	14.02	1.124E+00	4.931E+03
300	4.609	1.568E+01	2.292E+04
700	31.41	1.819E+01	1.140E+04
1000	35.15	1.188E+01	5.210E+03
3000	35.88	1.366E+01	1.997E+03
7000	42.11	3.493E+00	2.189E+02
10000	41.67	1.881E+00	8.248E+01
30000	42.04	1.894E+00	2.769E+01







Edge Energies:							
K	19999.5 eV	L_1	2865.5 eV	M_1	506.3 eV	N_1	63.2 eV
		L_2	2625.1 eV	M_2	411.6 eV	N_2	37.6 eV
		L_3	2520.2 eV	M_3	394.0 eV	N_3	35.5 eV
				M_4	231.1 eV		
				M_5	227.9 eV		

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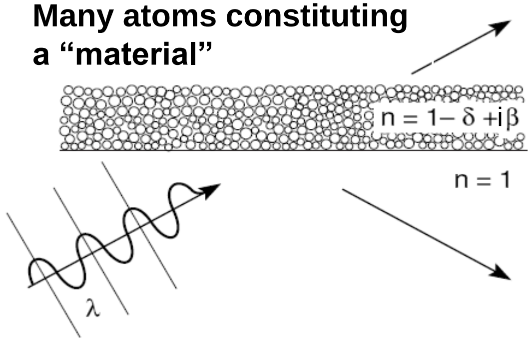
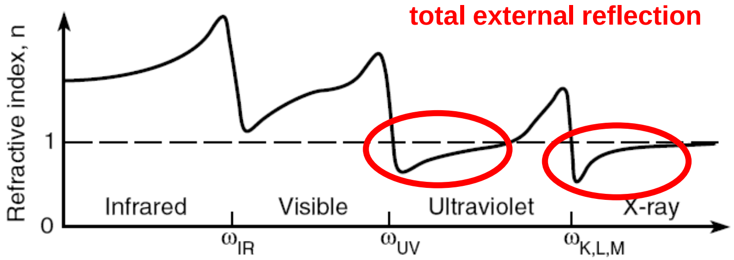
Index of refraction

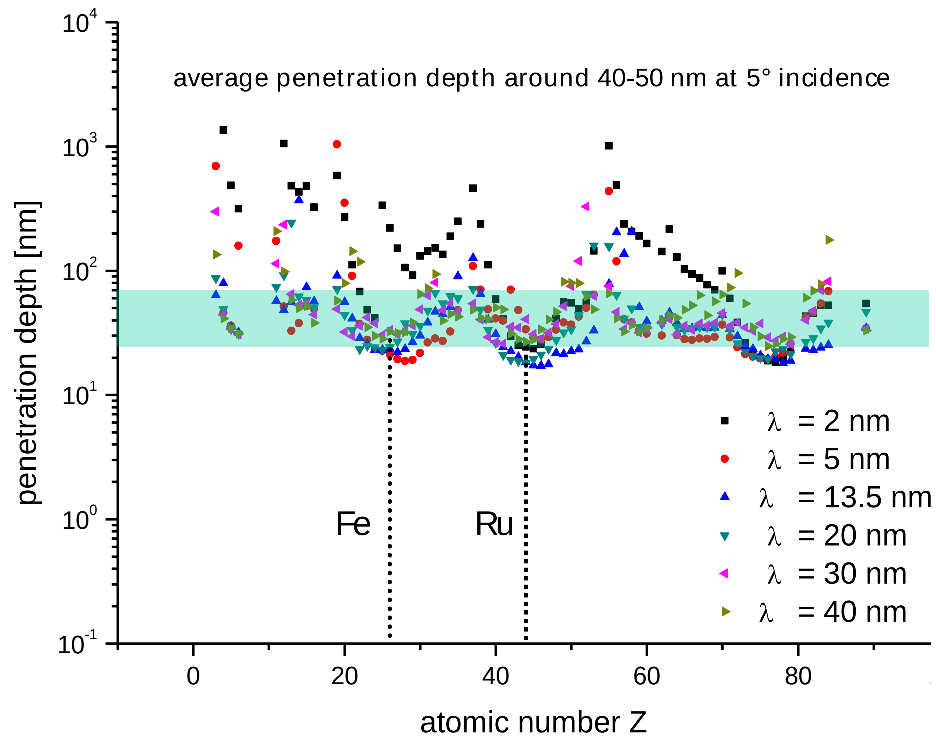
$$n(\omega) = 1 - \frac{n_a r_e \lambda^2}{2\pi} \underbrace{\left(f_1^0 - i f_2^0\right)}_{\text{complex atomic scattering factor}} = 1 - \delta + i\beta$$

$$\mathbf{E}(\mathbf{r}, t) = \underbrace{\mathbf{E}_0 e^{-i\omega(t - r/c)}}_{\text{vacuum propagation}} \underbrace{e^{-i(2\pi\delta/\lambda)r}}_{\phi\text{-shift}} \underbrace{e^{-(2\pi\beta/\lambda)r}}_{\text{decay}}$$

Many atoms constituting a "material"







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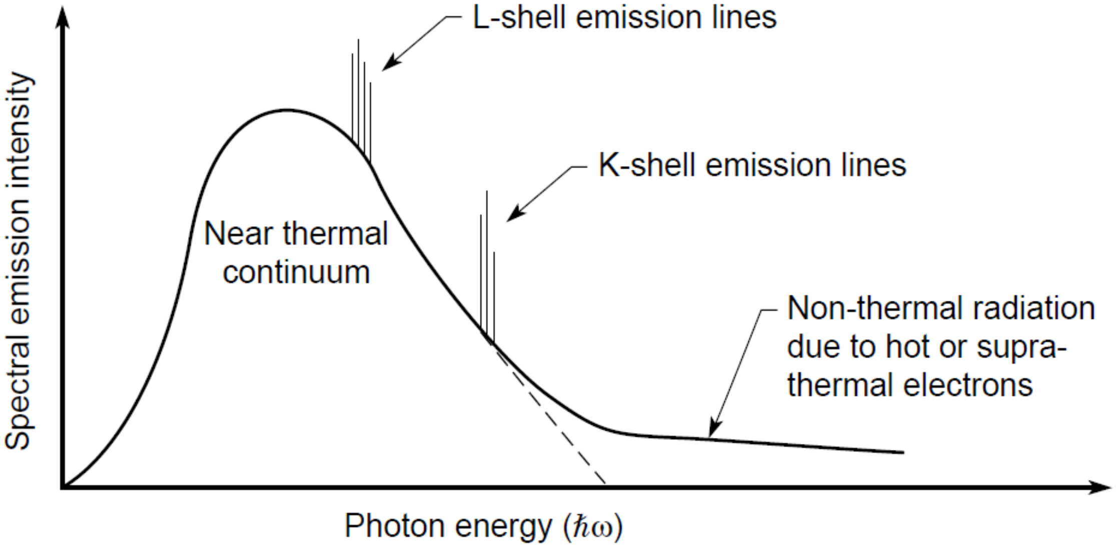
Radiation sources

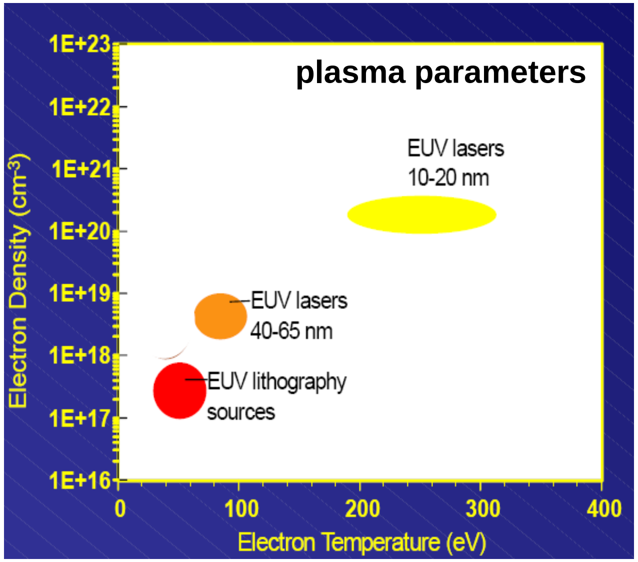
- **Synchrotron radiation (bending magnet, wiggler, undulator)**
- **X-ray tubes (e.g. Si L-edge at 100 eV)**
- **High Harmonic Generation**
- **Plasma based radiation sources**

1% x-ray, 99% heat due to infrared transitions of excited outer-shell electrons

highly ionized ions with outer-shell transitions in XUV (up to 90%)

$$P_{radiation} = P_{line} + P_{recombination} + P_{bremsstrahlung}$$





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Spectral properties

Xenon: [Kr]$4d^{10}5s^{2}5p^{6}$

Line emission from:

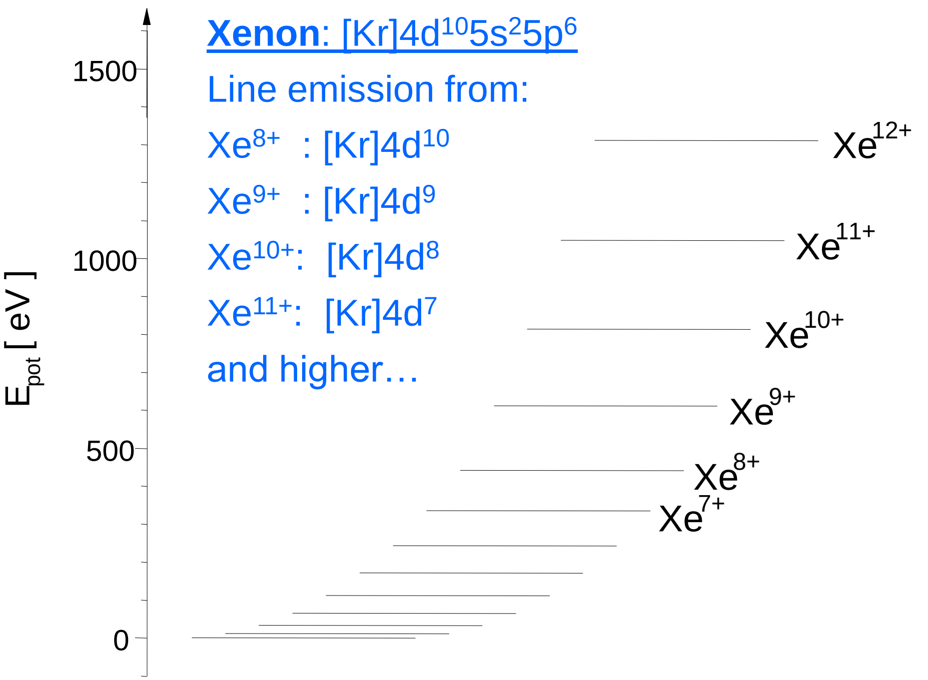
Xe^{8+} : [Kr]$4d^{10}$

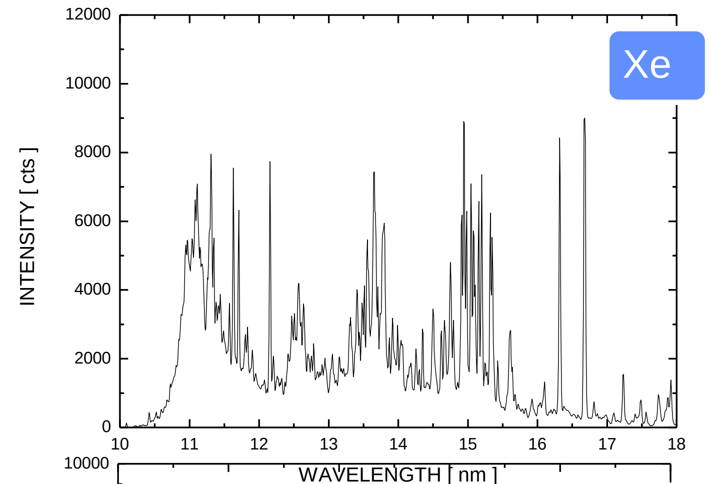
Xe^{9+} : [Kr]$4d^{9}$

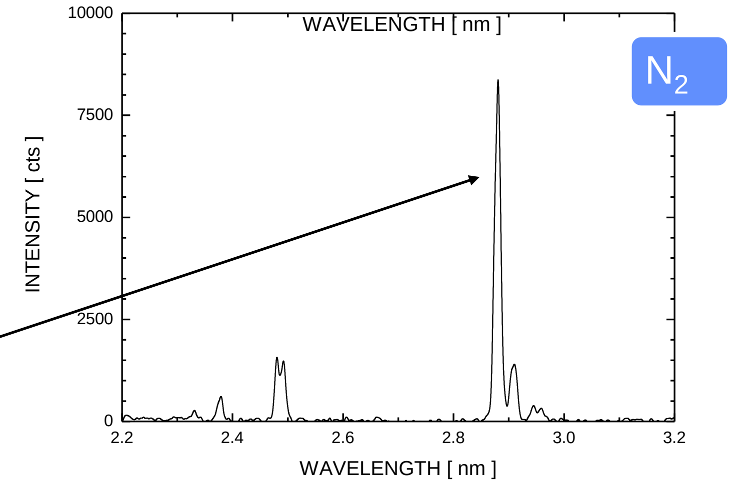
Xe^{10+}: [Kr]$4d^{8}$

Xe^{11+}: [Kr]$4d^{7}$

and higher…







N^{5+}: $1s^2$-1s2p line emission
used for soft x-ray microscopy

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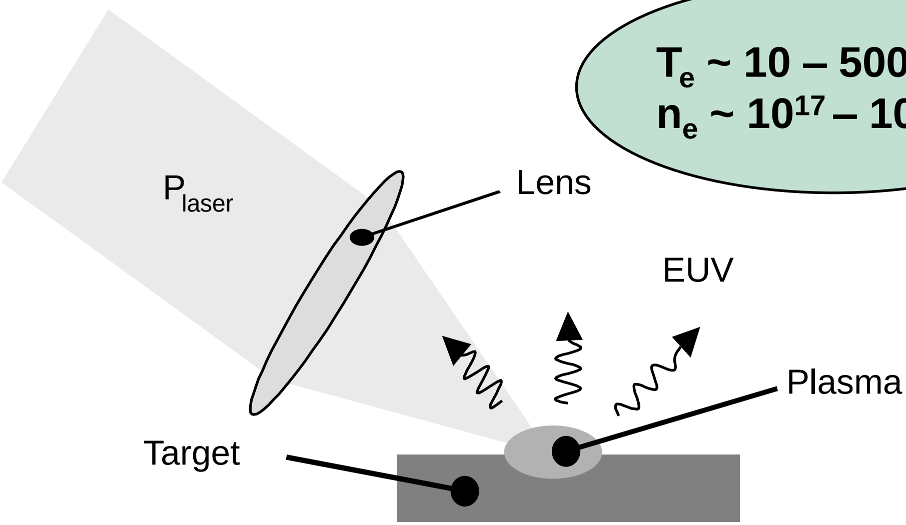
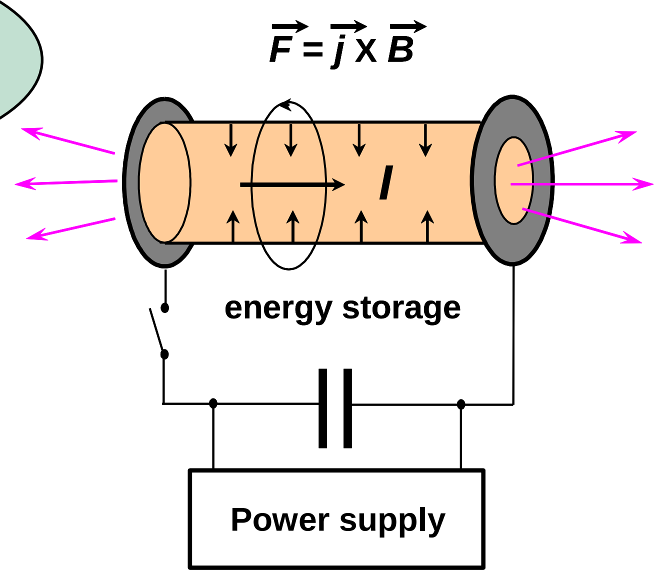
Technical realisation: LPP und DPP

Laser produced plasma



$T_e \sim 10 - 500$ eV
$n_e \sim 10^{17} - 10^{21}$ cm^{-3}

Discharge produced plasma



Typical parameters for laser and discharge produced plasmas

Parameter		LPP	DPP
Pulse duration	ns	0.2 – 10	10 – 100
Energy	J/Puls	0.25 – 1.5	2 – 10
Diameter	μm	50 – 100	100 – 500

- large technological progress within the last decade due to EUV lithography (up to 800W/2πsr @ 13.5 nm in 2% bw)
- commercial sources already available
- impact on laboratory scale applications

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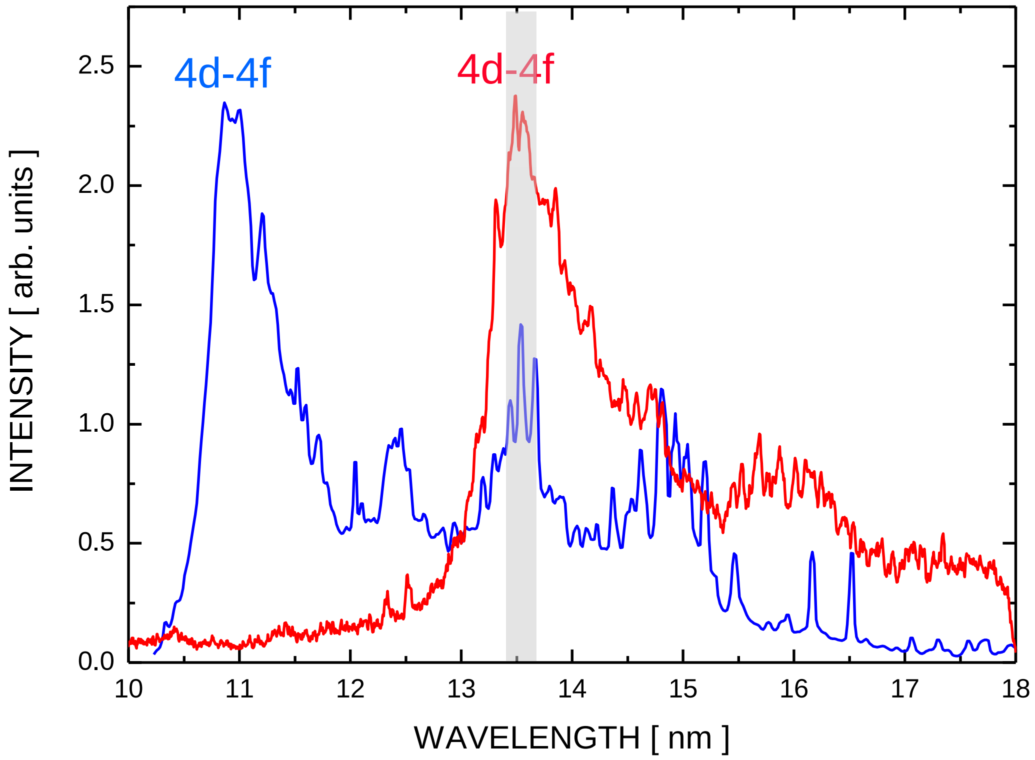
Emission spectrum at 13.5 nm

(strong self absorption of 4d-4f transitions!)



Xenon: [Kr]$4d^{10}5s^25p^6$

Line emission of:

Xe^{8+} : [Kr]$4d^{10}$

Xe^{9+} : [Kr]$4d^9$

Xe^{10+}: [Kr]$4d^8$

Xe^{11+}: [Kr]$4d^7$

and higher…

Tin: [Kr]$4d^{10}5s^25p^2$

Line emission of:

Sn^{8+} : [Kr]$4d^6$

Sn^{9+} : [Kr]$4d^5$

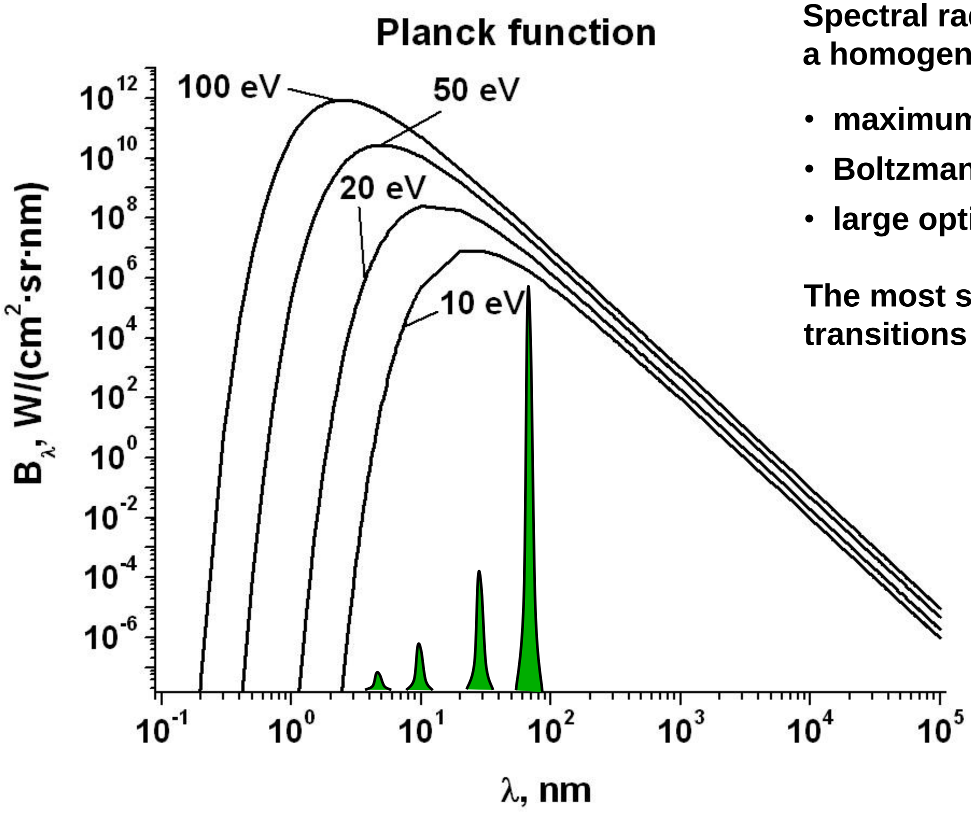
Sn^{10+}: [Kr]$4d^4$

Sn^{11+}: [Kr]$4d^3$

and higher….

Pseudo-Planck emitter

Pseudo-Planck emitter: radiation source, whose emission in a spectrally limited interval reaches the Planck curve, not however necessarily for the entire and/or a broader range

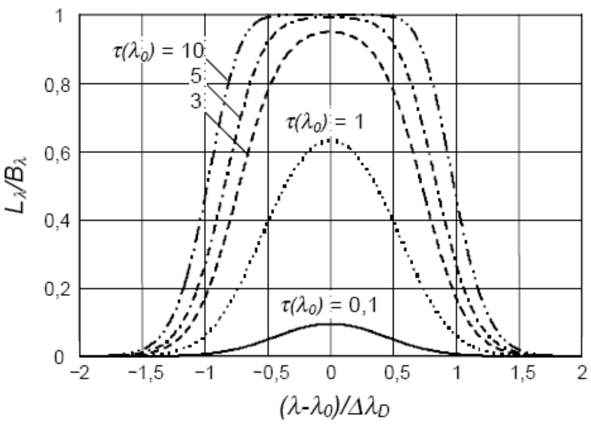


Spectral radiance L_λ at the surface of a homogeneous radiating plasma: $L_\lambda = S_\lambda \cdot \left(1 - e^{-\tau(\lambda)}\right)$

- **maximum possible radiance for T_{plasma} in steady state**
- **Boltzmann distribution of population densities required**
- **large optical thickness over the line of sight required**

The most suitable candidates in XUV: Resonance transitions

Opacity influence on line profile



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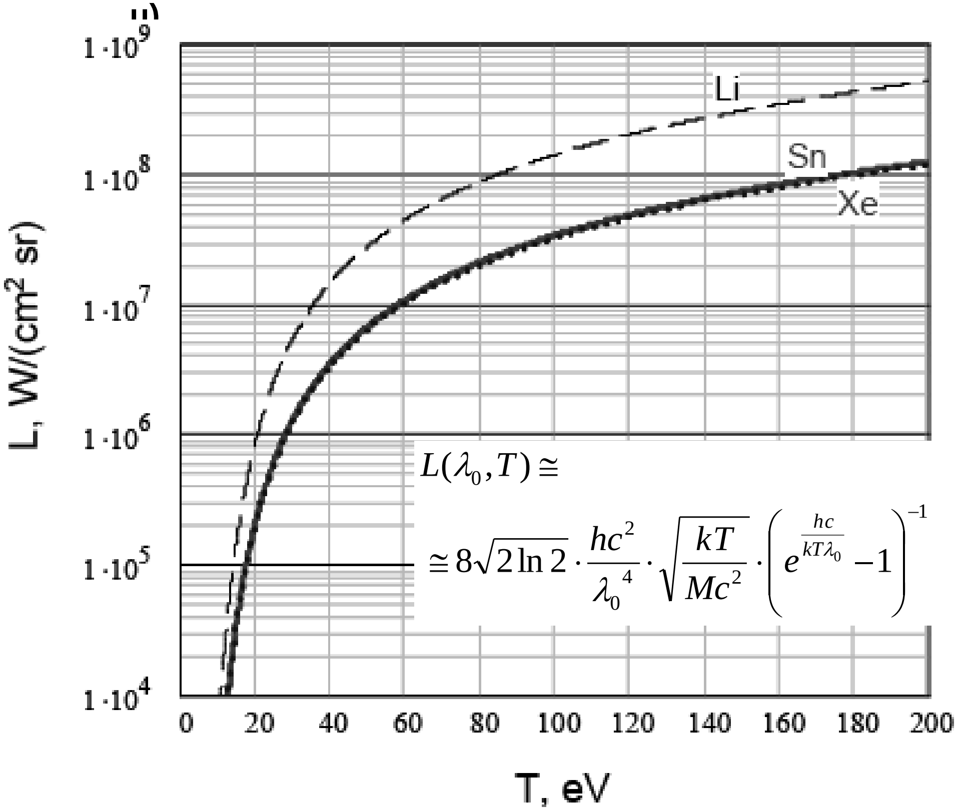
Possible line intensities

Radiance of one optically thick line ($\Delta\lambda_{1/2} \sim 2\Delta\lambda_{Doppler}$) at 13.5 nm for Li (6.94 u), Sn (118.7 u) and Xe (131.3 u)



- **useful for rough estimate of maximum power**
- **electron temperature has to match ionization level balance (avoid over-ionization)**
- **electron density ensuring Boltzmann distribution and opacity**
- **optimizing by increasing T_e possible in transient plasmas, especially for lower densities**
- **resonance UTA with broader spectral range and corresponding higher radiation power**
- **increasing of lifetime for higher radiation energy**

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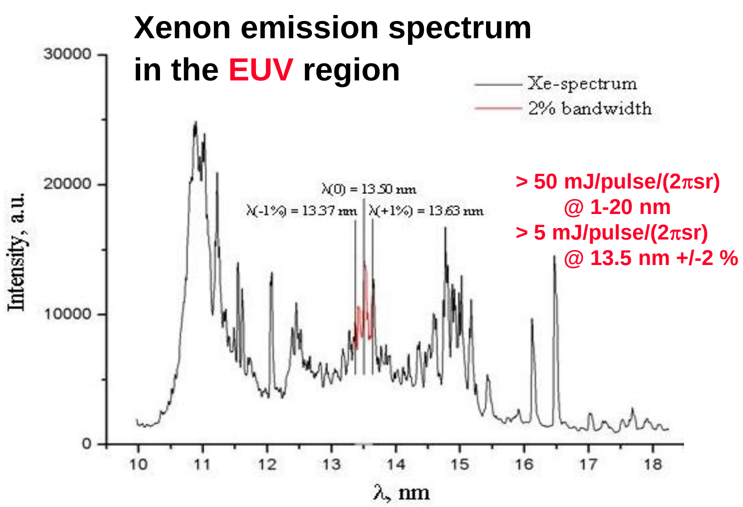
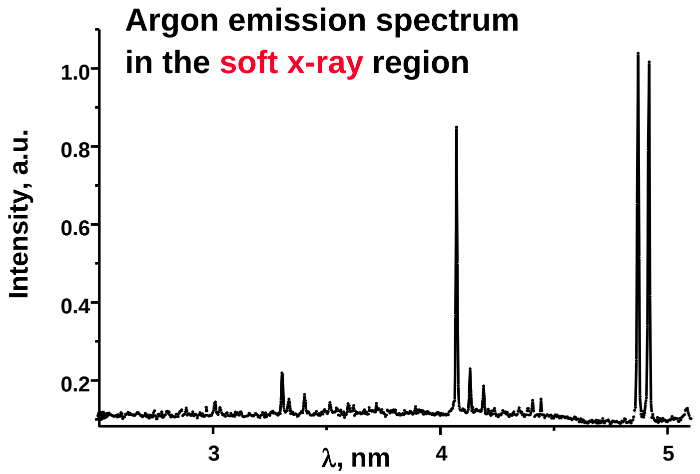
Laboratory scale plasma-based XUV sources





basic physics:

- emission spectrum consists of single lines or bunches of lines (UTA, quasi-continuum) of high ionized ions depending on plasma parameters, composition and dynamics
- XUV lasers exist - more sophisticated to achieve plasma parameters
- emission always pulsed, max. few 100 ns

technological aspects

- LPP and DPP with main differences in diameter and pulse duration
- large technological progress within the last decade due to EUV lithography (up to 800W/2πsr @ 13.5 nm in 2% bw)
- commercial sources already available
- impact on laboratory scale applications

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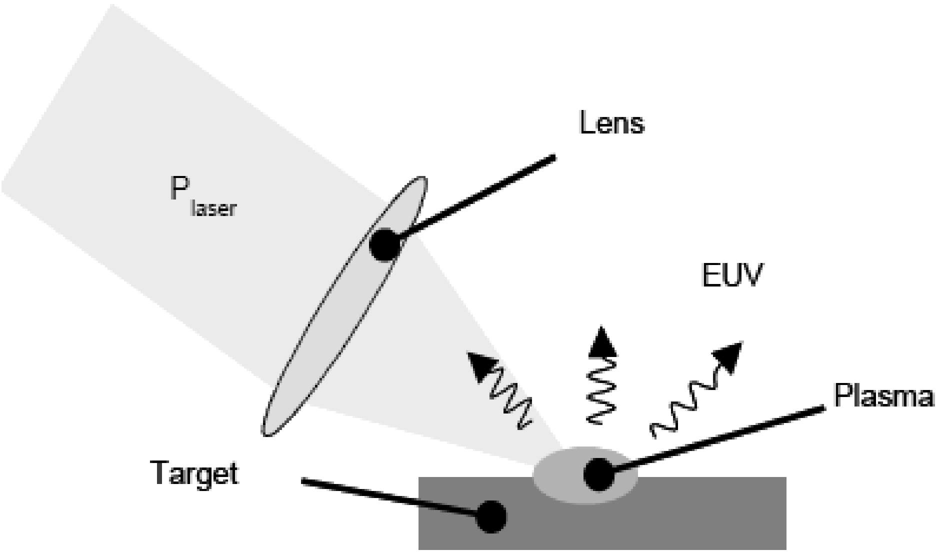
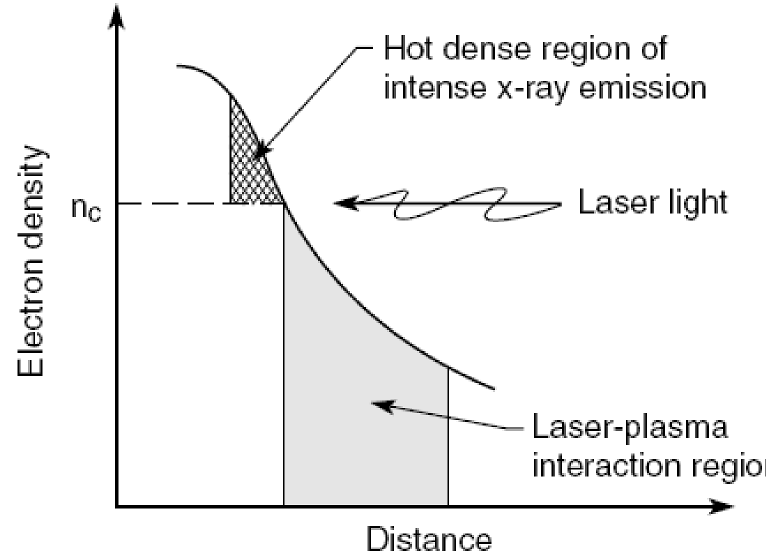
Laser produced plasmas for EUV radiation





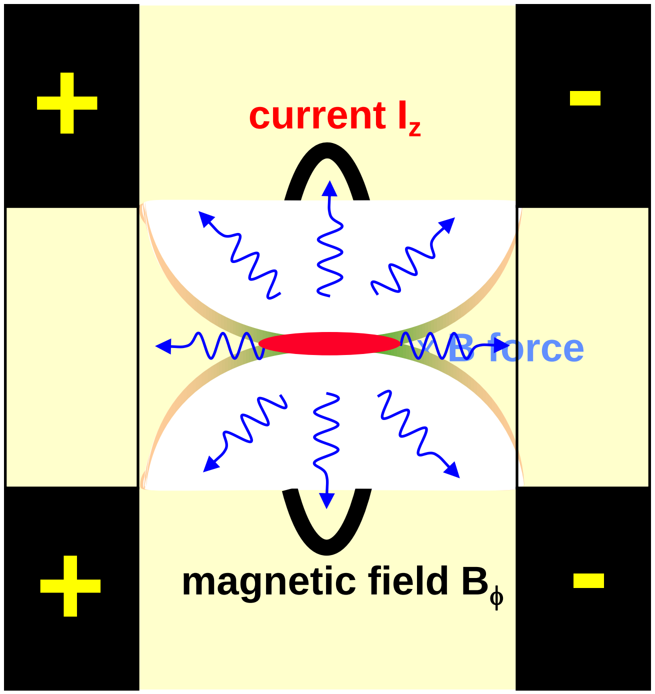
A laser beam is focused onto a target with intensities around 10^{11} W/cm^2. The laser light converts neutral target material into a hot and dense plasma by the inverse bremsstahlung mechanism. The emitted EUV light depends on the chemical and physical composition of the target (elements, phase, size) and the laser parameters (pulse duration, wavelength, intensity).

- $\kappa T_e \sim 50$ eV to 1 keV
- $n_e \sim 10^{20}$ to 10^{22} e/cm^3

$$n_{crit} = \frac{\epsilon_0 m_e \omega_L^2}{e^2} = \frac{1.11 \times 10^{21}}{(\lambda_L/[\mu\mathrm{m}])^2} \qquad [\mathrm{cm}^{-3}]$$

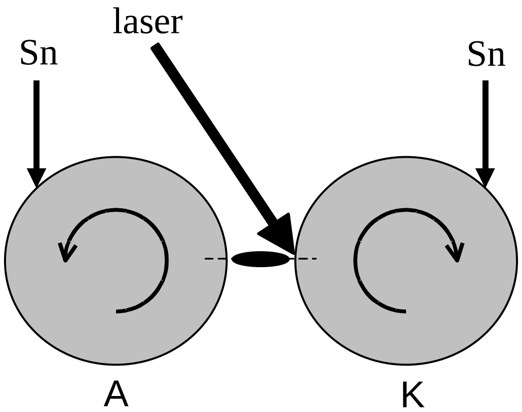
$$T_e = 2.85 \times 10^{-4} \times \left(I_L/[\mathrm{W/cm}^2]\right)^{4/9} \qquad [\mathrm{eV}]$$

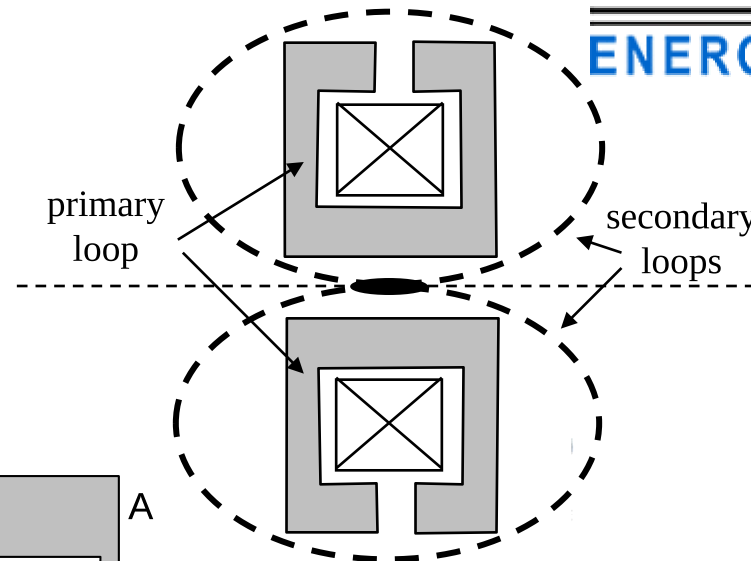
Discharge plasmas for EUV radiation



• Plasmatemperatur	(T_e)	> 20 eV
• Plasmadichte	(n_e)	> 10^{18} cm^{-3}
• Neutralgasdruck	(p)	10 - 100 Pa
• Peakstrom	(I_{max})	10 - 20 kA
• Pulsdauer	(t_p)	einige 100 ns
• Stromdichte	(j)	10^4 - 10^5 A/cm^2
• Pulsenergie	(E)	1 - 10 J
• Abmessungen	(d)	mm - cm

Commercial EUV sources





ENERGETIQ

PHILIPS

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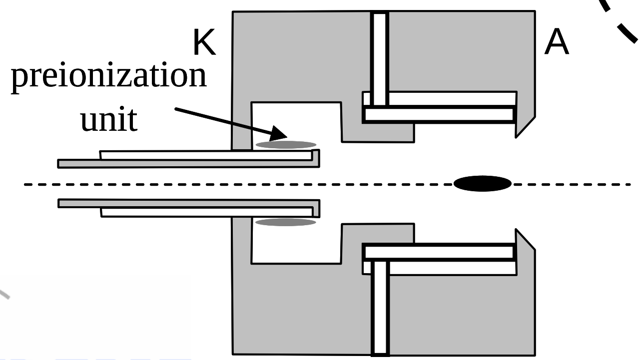
Fraunhofer Institut Lasertechnik



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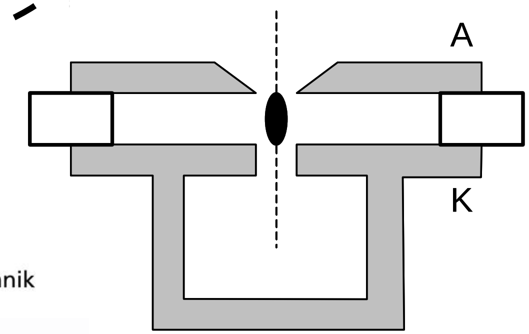

AIXUV EUV-Technology

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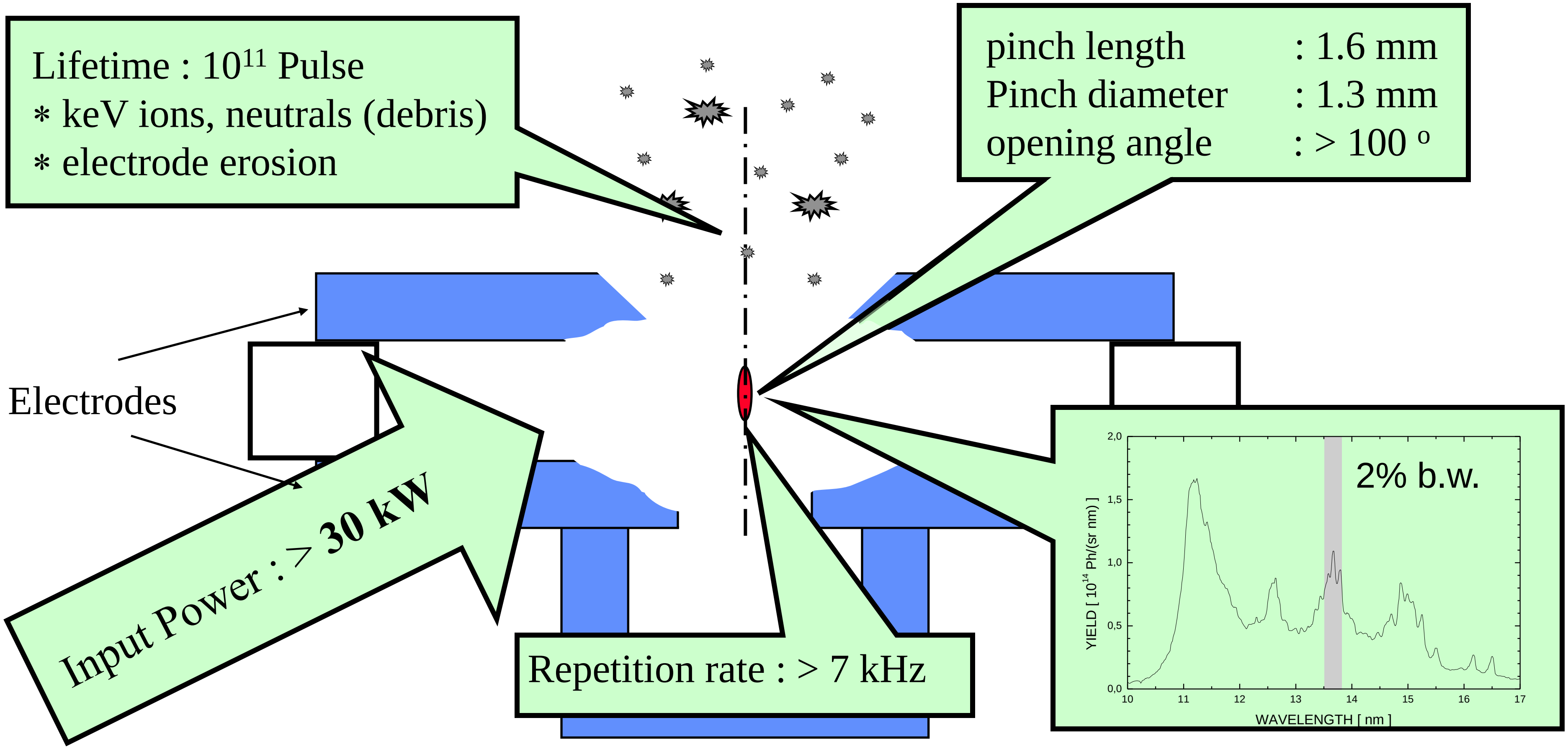
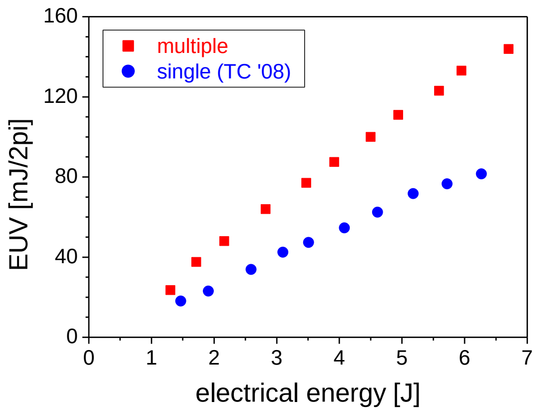
Challenges due to EUV lithography



References : Sematech Symposia, Antwerp 2003, Dallas 2002

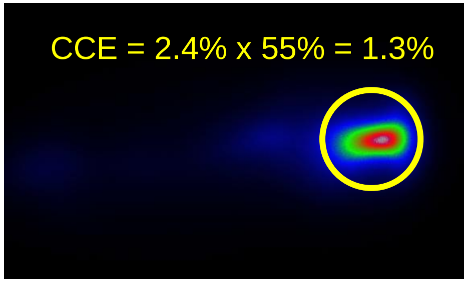
Power scaling

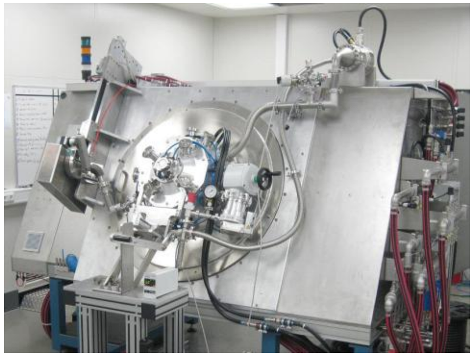
Tin vacuum arc

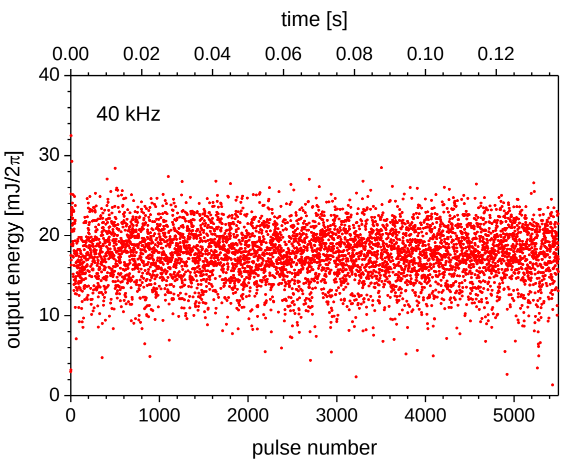


Increase of conversion efficiency by factor >2

Improvemnet of collection efficiency smaller source size

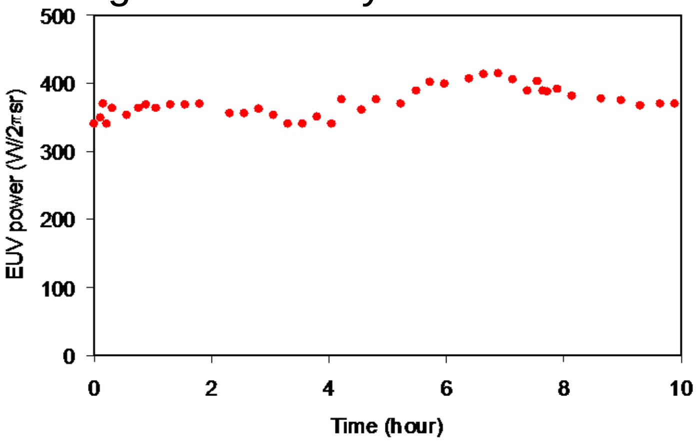






Power-
frequency scaling

Long term stability



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EUV sources in Aachen

N_2

Wavelength λ= 2.88 nm (430 eV)
Repetition Rate: 1 – 2 kHz
Photon Flux: $1*10^{14}$ Ph/2πsr

Fraunhofer ILT

Repetition rate up to 4 kHz
EUV (10 – 20 nm): > 400 W/2πsr
EUV (13.5 nm, 2% bw): 65 W/2πsr

Xe

Xe

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Sn

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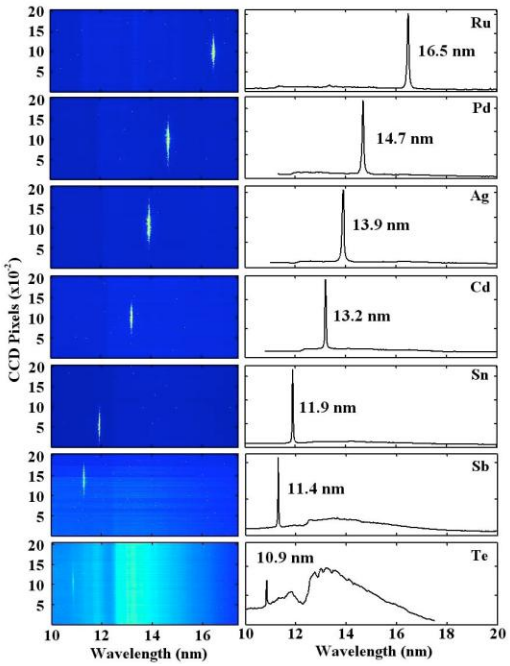
Laboratory EUV sources - Coherent

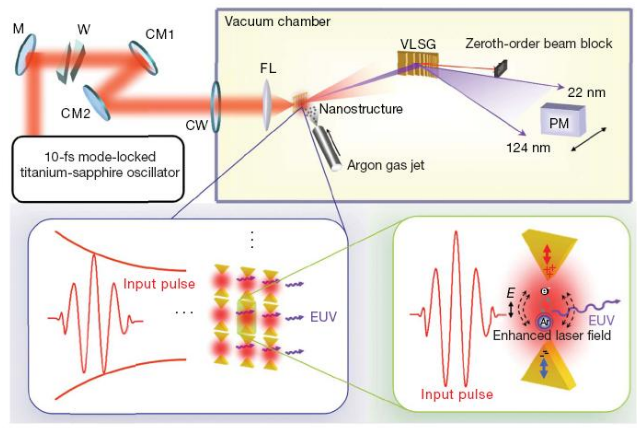
Direct lasing



P~1 µW

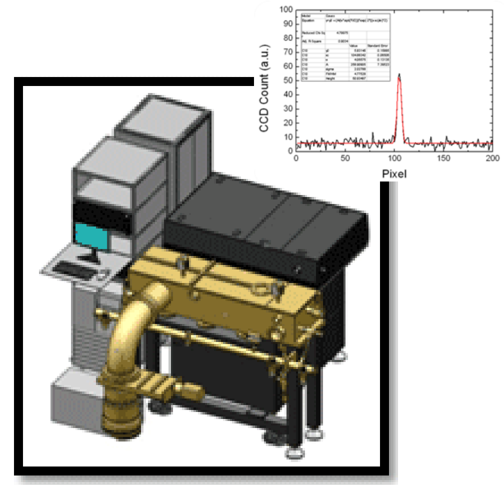
*J. Rocca, Colorado State University

High-order harmonic generation in an atomic gas ionized by a fs laser pulse.



P~ 1 nW

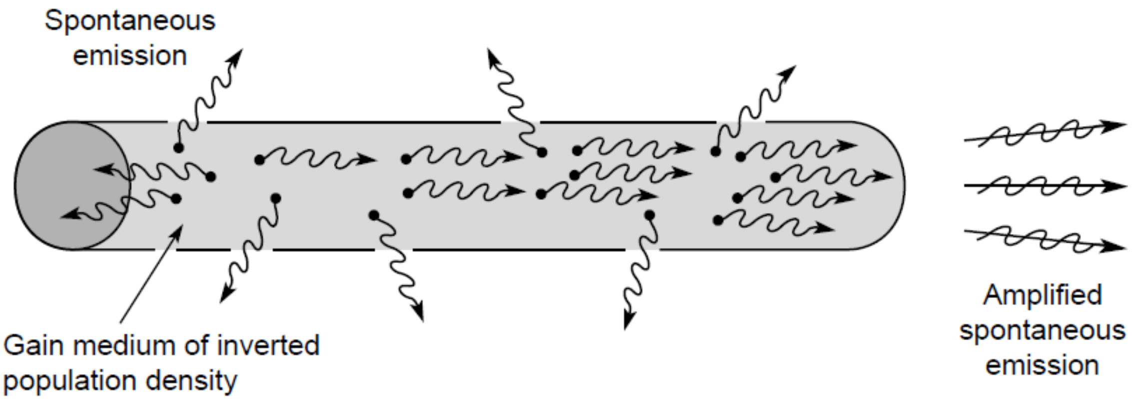
*S.Kim et al, Nature 453,757 (2008)

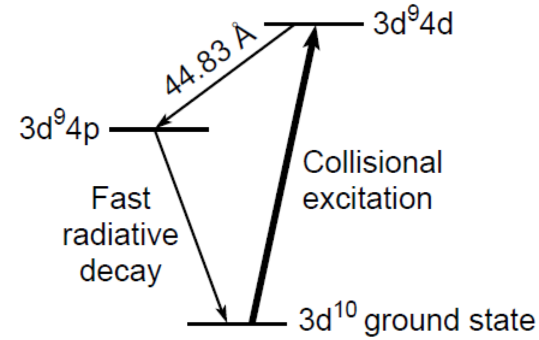


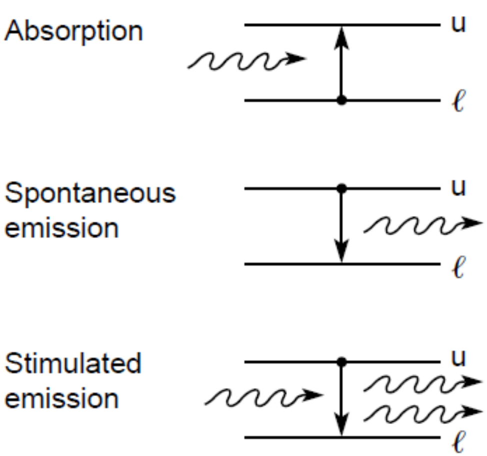
P= 48 nW

*FST Co. & Samsung (2011)

Extreme Ultraviolet and Soft X-Ray Lasers





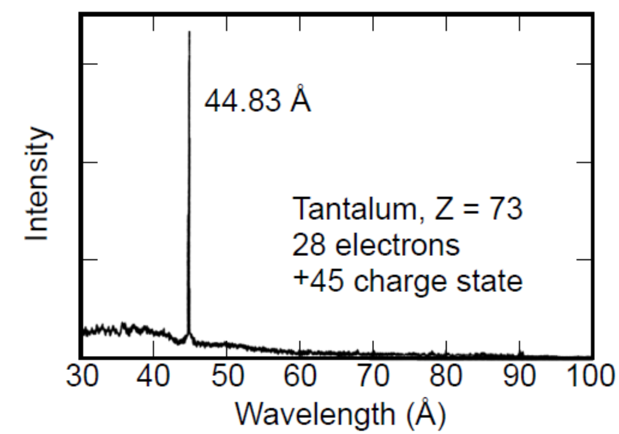


$$\frac{I}{I_0} = e^{GL}$$

$$G = n_u \sigma_{\text{stim}} F$$

$$\sigma_{\text{stim}} = \frac{\pi \lambda r_e}{(\Delta\lambda/\lambda)} \left(\frac{g_l}{g_u}\right) f_{lu}$$

$$\frac{P}{A} = \frac{16\pi^2 c^2 \hbar (\Delta\lambda/\lambda) GL}{\lambda^4}$$



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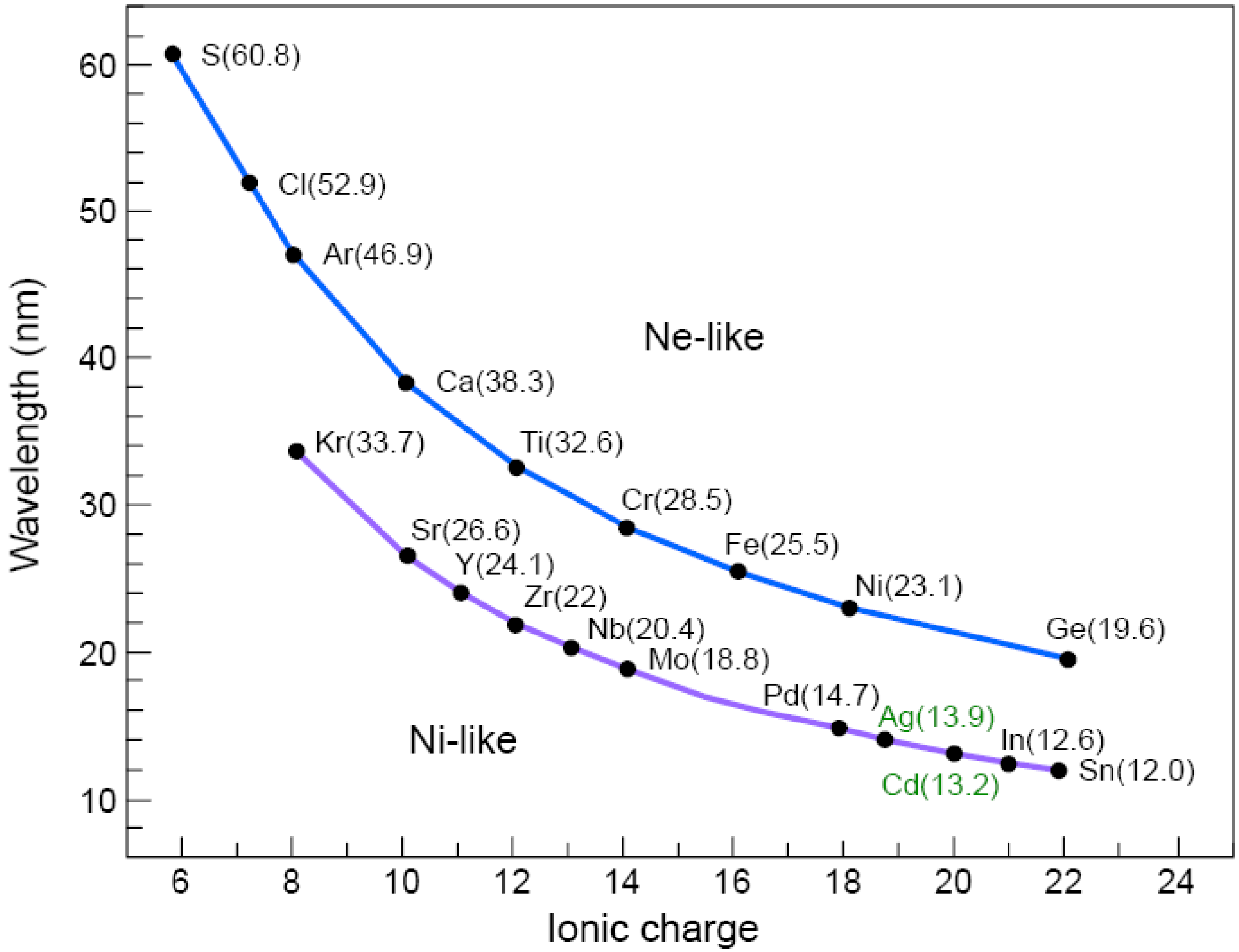
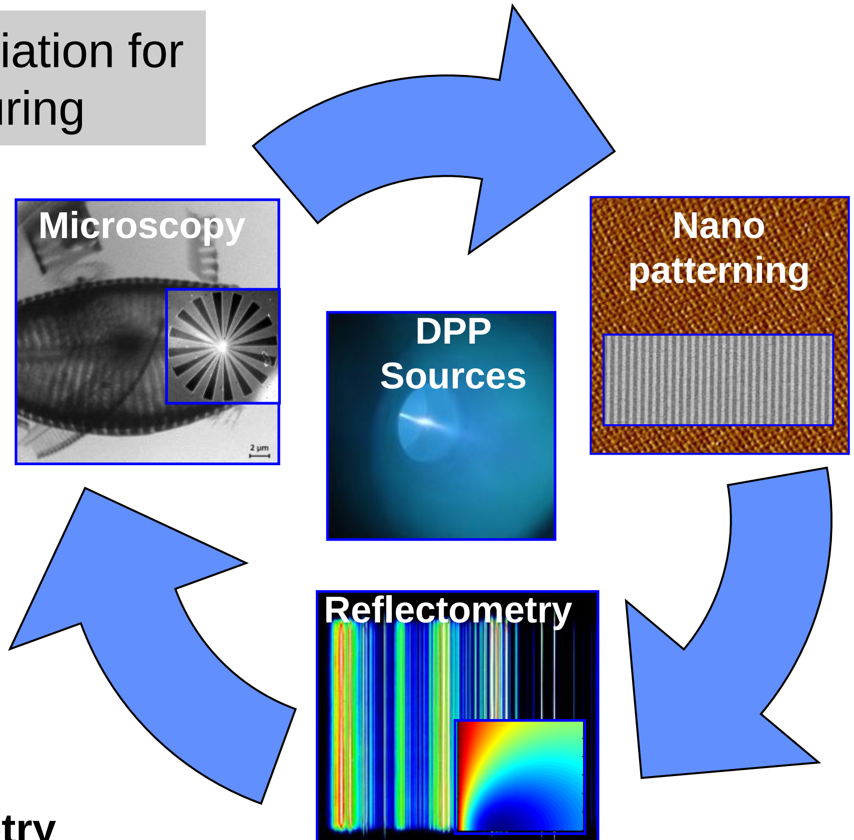
Scaling to 13 nm Requires Excitation of Ni-Like Cd Ions (Cd + 20)



Research Activities of EUV Technology Group at TOS/ILT

Utilization of EUV radiation for metrology and structuring



Microscopy
- Defect detection
- EUV mask inspection
- Water window microscopy (ILT)

see smaller features

Lithography
- Nanostructuring of surfaces with laboratory sources
- Patterning of structures < 10 nm

write smaller patterns

Reflectometry
- Analysis of nanolayers and surfaces
- Layer thickness and roughness measurement
- Elemental composition

analyze with elemental and chemical sensitivity

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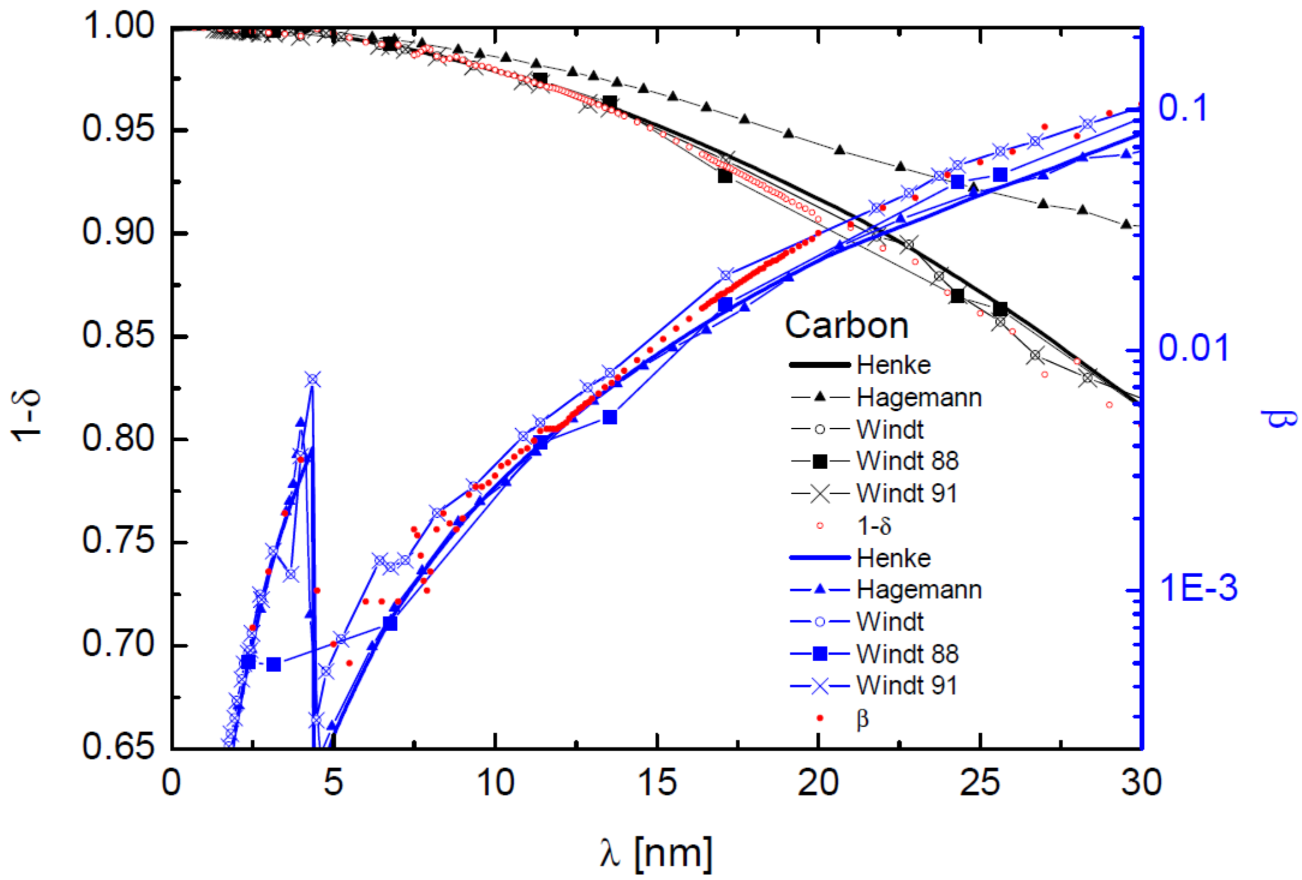
Database build-up for relevant materials

Refractive index determination in XUV from multi-angle reflectivity measurements at 3°,4°,5°,12°,15°



$$n = 1 - \delta + i\beta$$

$$\delta = \frac{r_e \lambda^2 N_A \rho}{2\pi M} f_1^0(\omega)$$

$$\beta = \frac{r_e \lambda^2 N_A \rho}{2\pi M} f_2^0(\omega)$$

$$f_1^0 - i f_2^0 = \sum_{s=1}^{Z} \frac{\omega^2}{\omega^2 - \omega_s^2 + i\gamma\omega}$$

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Benchmarking: XUV als Metrology Tool

Technique	In	Out	Property monitored	destructive	Non-destructive	Vacuum	Typ. Depth of Analysis Typ. Spatial Resolution	Typ. Measuring time
Ellipsometry	Photon	Photon	polarization		•	-	> 5nm (not all mat.) 1-100 µm	ms – s
XRR	Photon	Photon	Intensity		•	-	>>100 nm > 50 µm	minutes – hrs
AFM	-	-	Deflection	•	•	-	Surface only 0.1 – 10 nm	Hours
TEM	Electron	Electron	Intensity	•		<1E-8	~ 100 nm thin films << 1 nm	Sec-min
SEM	Electron	Electron	Intensity		•	<1E-8	Surface only ~ 1 - 5 nm	Sec-min
XPS	Photon	Electron	Energy		•	<1E-8	10 nm > 50 µm	>hour
AES	Photon	Electron	Energy		•	<1E-9	1- 3 nm 50 nm	>hour
RBS	Ion	Ion	Energy	•		1E-6 - 1E-9	1 µm 1 mm	minutes – hrs
SIMS	Ion	Ion	Mass	•		1E-6 - 1E-9	1 – 10 nm 1 mm – 0.5 µm	minutes – hrs
GIXUVR	Photon	Photon	Intensity		•	1E-2 - 1E-6	< 100 nm ~ µm – nm	ms – s

Benchmarking: XUV als Metrology Tool

Technique	In	Out	Property monitored	destructive	Non-destructive	Vacuum [mbar]	Typ. Depth of Analysis Typ. Spatial Resolution	Typ. Measuring time
Ellipsometry	Photon	Photon	polarization		•	-	> 5nm (not all mat.) 1-100 µm	ms – s
XRR	Photon	Photon	Intensity		•	-	>>100 nm > 50 µm	minutes – hrs
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SIMS	Ion	Ion	Mass	•		1E-6 - 1E-9	1 – 10 nm 1 mm – 0.5 µm	minutes – hrs
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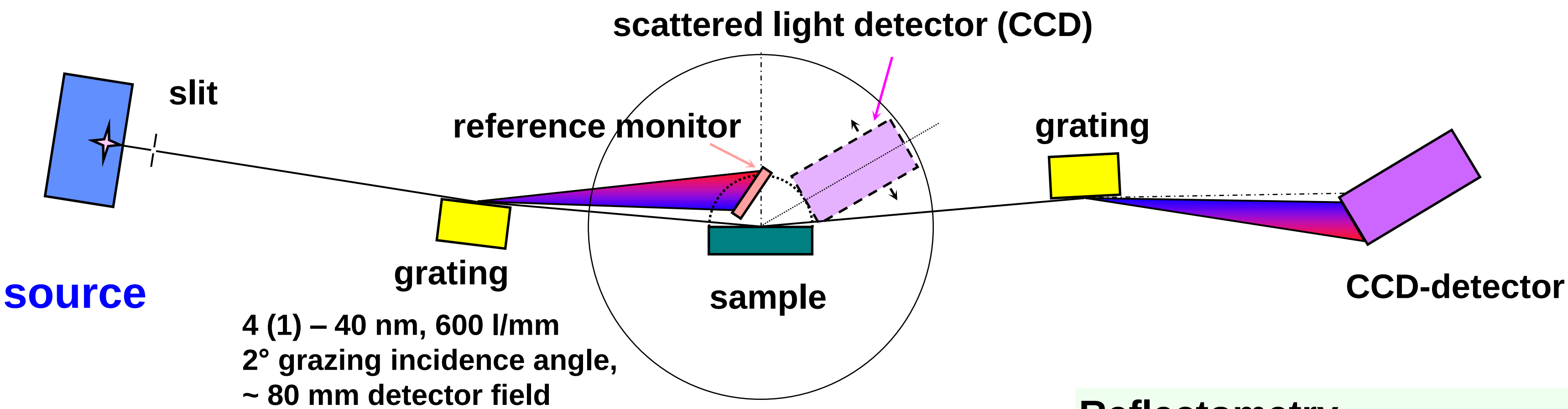
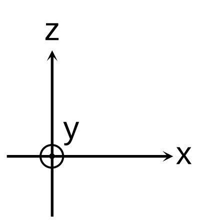
Set-up for grazing incidence reflectometry



sample chamber



Reflectometry

Determination of thin film thicknesses, roughnesses and elemental composition

Determination of atomic scattering factors

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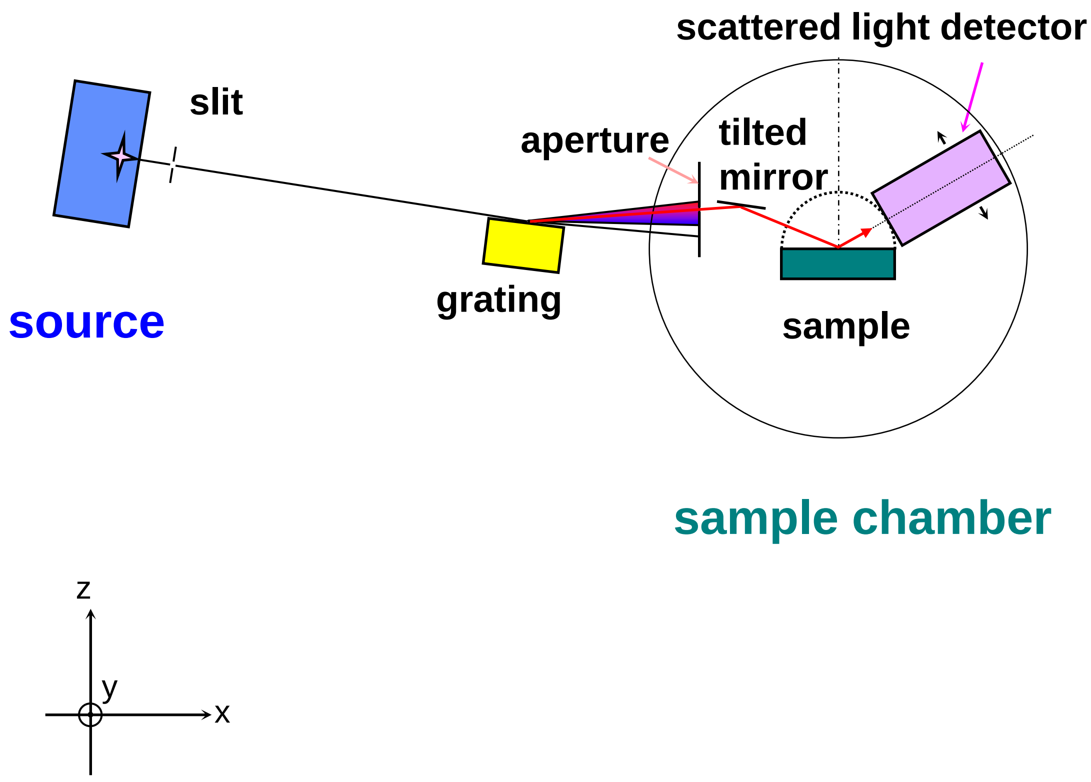
Set-up for scatterometry, diffractometry and lens-less imaging



Scatterometry / diffractometry
- Characterization of surface and layer roughnesses or nano-patterned arrays

Microscopy in grazing incidence (with a zone plate)

Lens less imaging

With a multilayer mirror polarizer at Brewster's angle
- Ellipsometry
- Magnetic layers / structures

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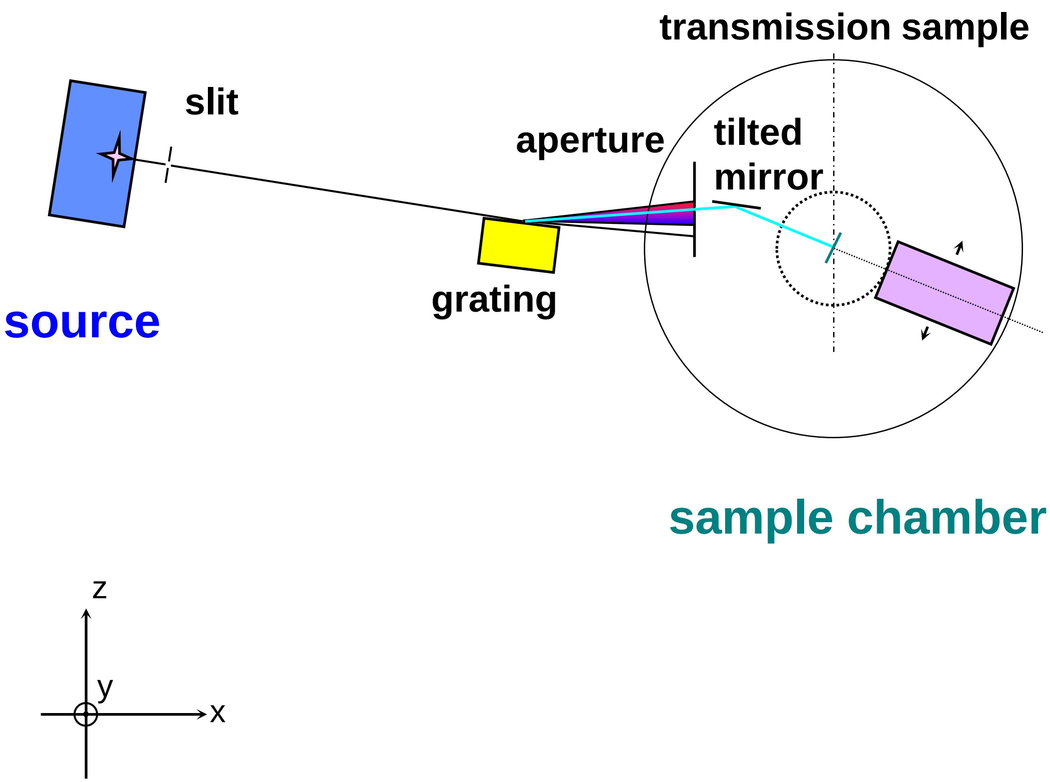
Set-up for scatterometry, diffractometry and lens-less imaging



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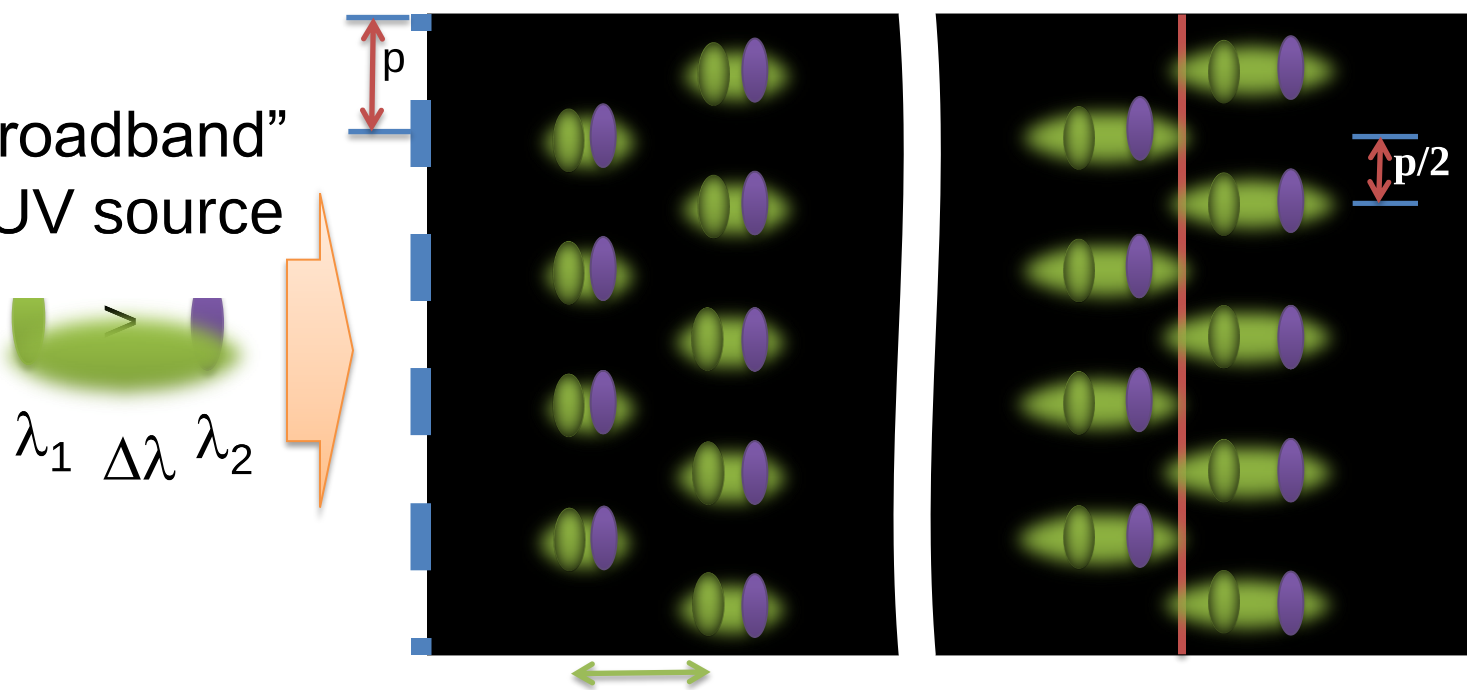
Relevant lengths for EUV-IL

	Length	Significance
Wavelength	~10-15 nm	Spatial resolution of aerial image
Absorption length	~50-100 nm	Exposable film thickness, surface sensitivity
Photo/secondary electron path length	< 1nm	Blur, proximity effect
Average distance between photo-absorption events	~2.5nm (for dose 1000J/cm^3, E_{ph}=92.5eV)	Statistics, roughness
Recording medium/process	?	Molecular size, diffusion, dissolution

H. Solak, MNE07, Copenhagen, 26 Sep 07

Possible schemes for EUV-IL - Talbot



$$L_{Talbot} = \frac{2p^2}{\lambda}$$

$L_{Talbot1}/2$

$L_{Talbot2}/2$

Achromatic Talbot effect

*N.Guerineau (2000), H.Solak (2005)

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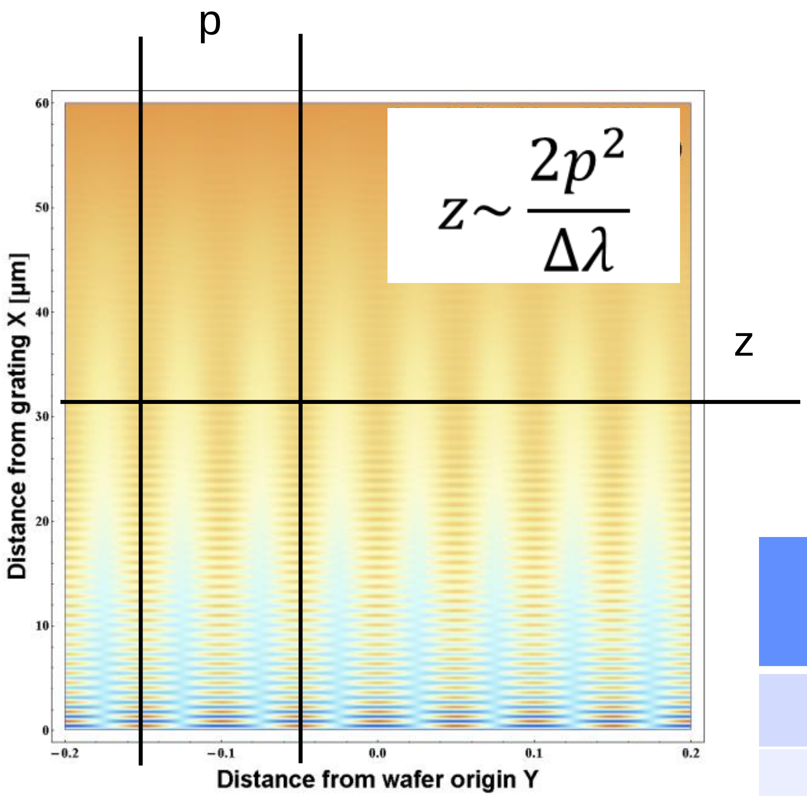
Talbot self-imaging



Requirements	
Bandwidth	Spatial coherence
$\Delta\lambda \sim 2\text{-}4\%$	$> 4p\frac{\lambda}{\Delta\lambda}$

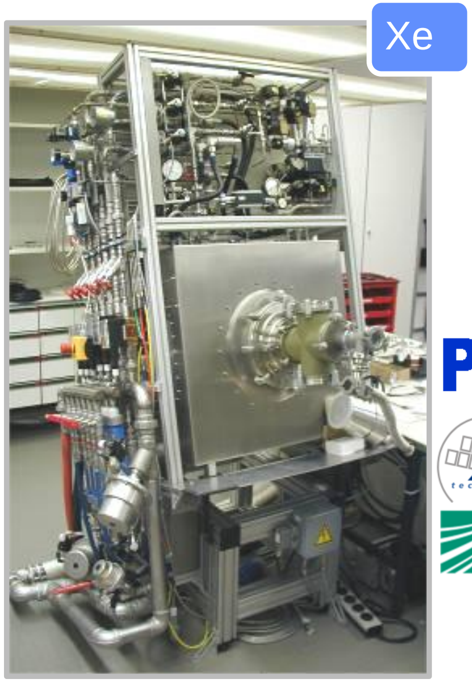
Mask period	Bandwidth @11nm	Required coherence
100 nm	3.2 %	12.5 µm
40 nm	3.2 %	5 µm

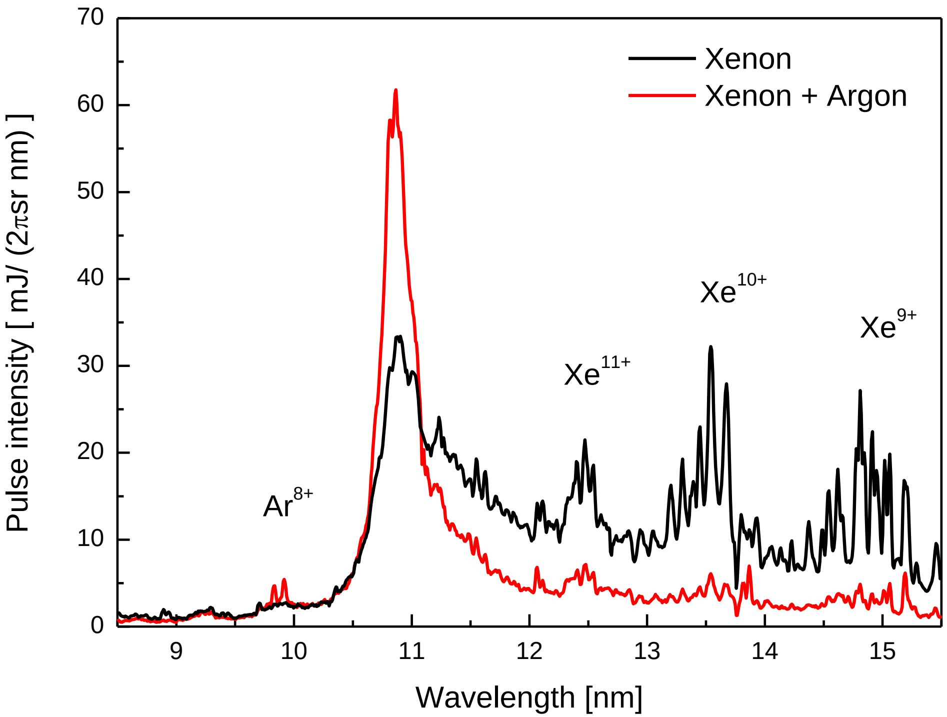
DPP EUV source

Repetition rate up to 4 kHz

EUV (10 – 20 nm): > 400 W/2πsr

EUV (13.5 nm, 2% bw): 65 W/2πsr





PHILIPS

XTREME technologies

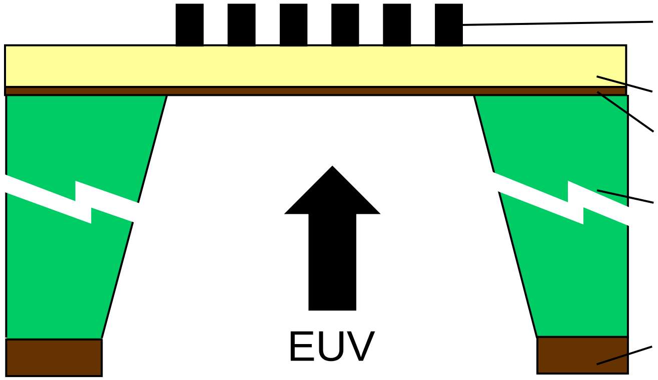
Fraunhofer ILT

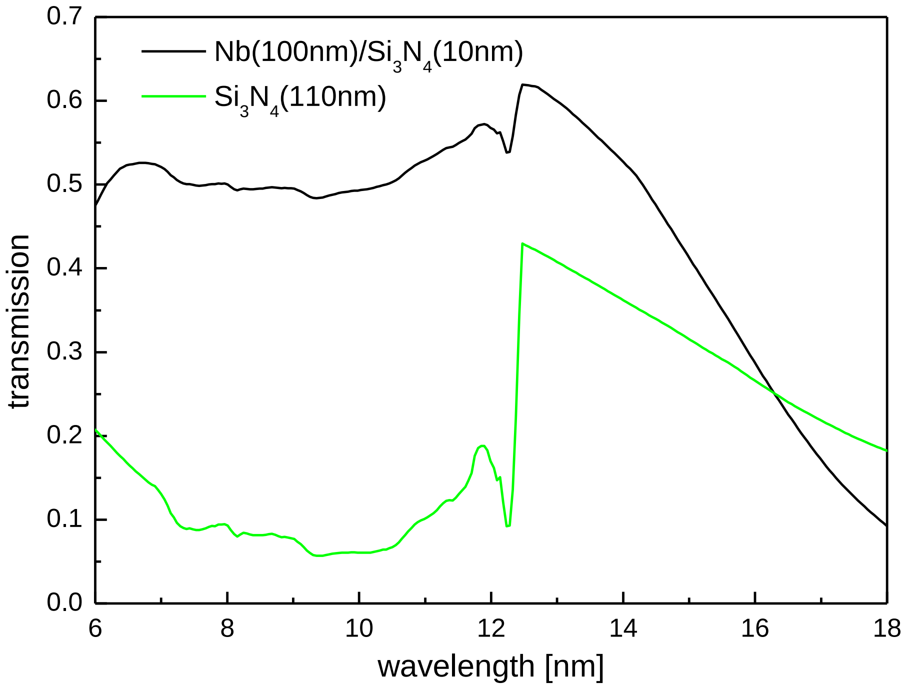
Admixture of Ar to Xe plasma allows to supress 12-16 nm lines resulting in radiation at 10.9 nm with 3.2% bw

K. Bergmann, S.V. Danylyuk, L. Juschkin, J. Appl. Phys. V.106, 073309 (2009)

Transmission masks

For wavelengths < 12.4nm conventional Si_3N_4-based technology is no longer efficient due to high silicon absorption





- Flat Nb membranes with size up to 4 mm^2 are achieved
- Resist patterned with 50 keV e-beam lithography
- Pattern transferred to ~80 nm thick nickel by ion beam etching
- EUV 1^{st} order diffraction efficiency ~9-9.5%

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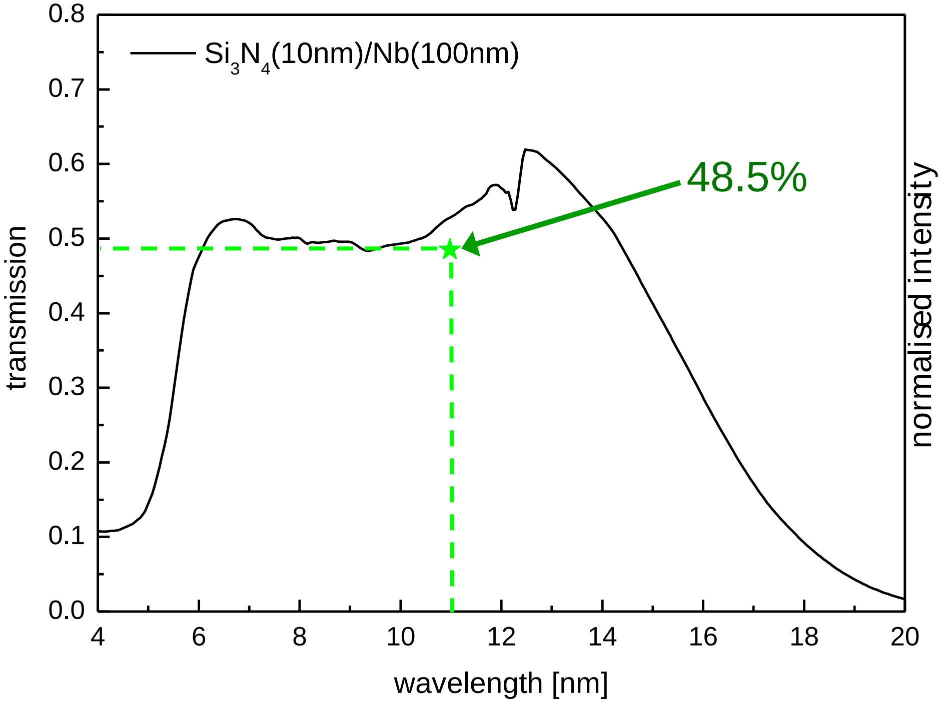
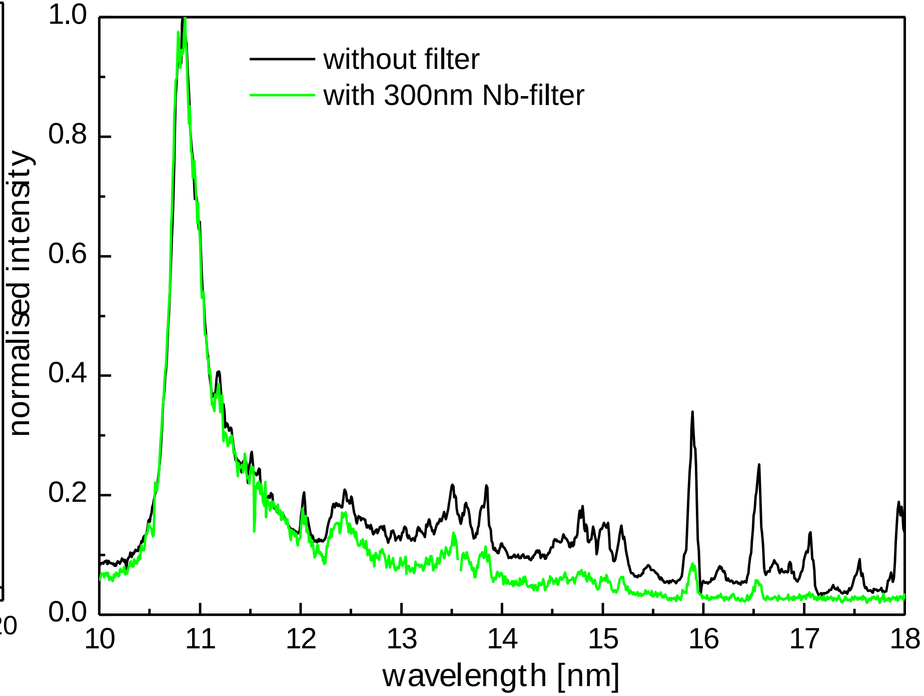
Transmisson measurements

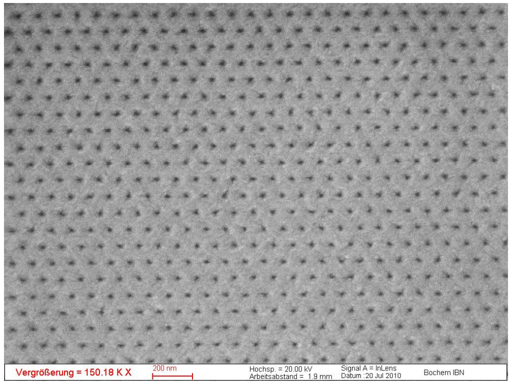




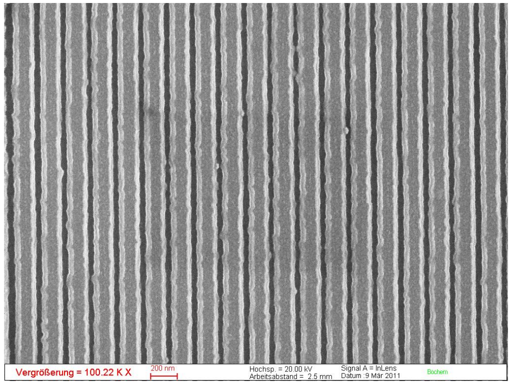
Theoretical transmission curves of the investigated membrane and measured transmittance at 11nm

Emission spectrum of DPP source with Xe/Ar gas mixture measured with and without 300nm Nb-filter

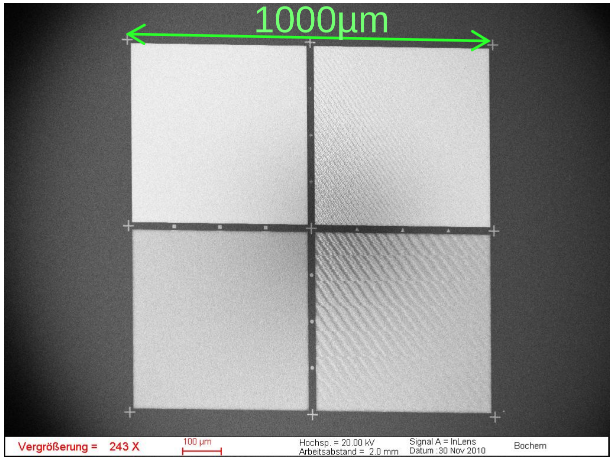
Mask Patterns



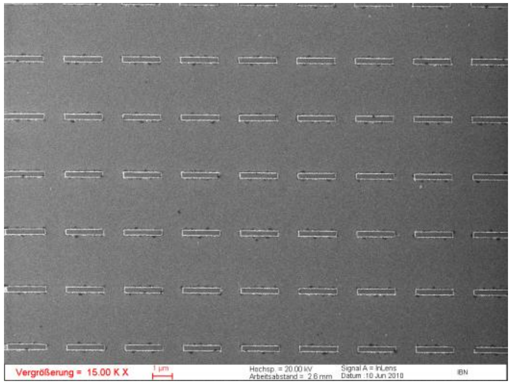
hex. pinhole array: p=100nm, dia.=40nm; scale=200nm



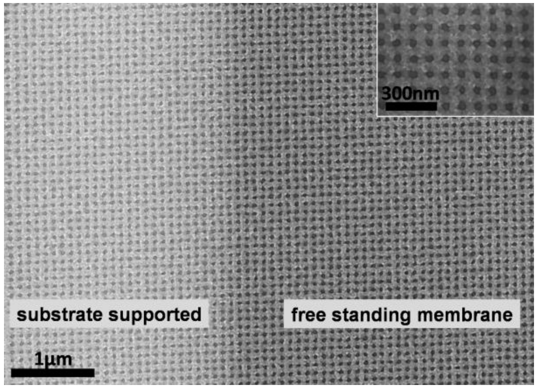
L/S array: p=200nm, lines=160nm, spaces=40nm; scale=200nm



mask layout incl. markers; scale=100µm

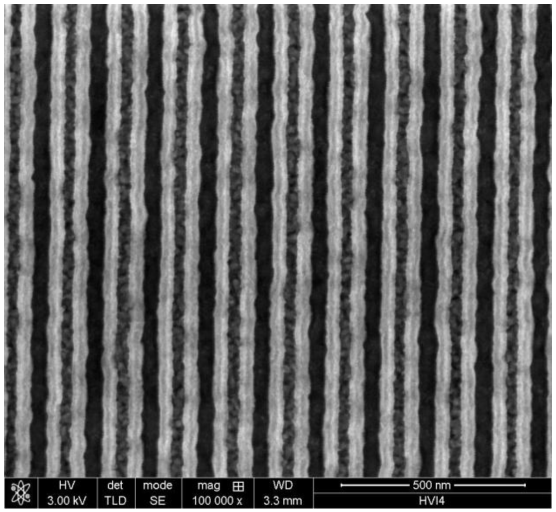


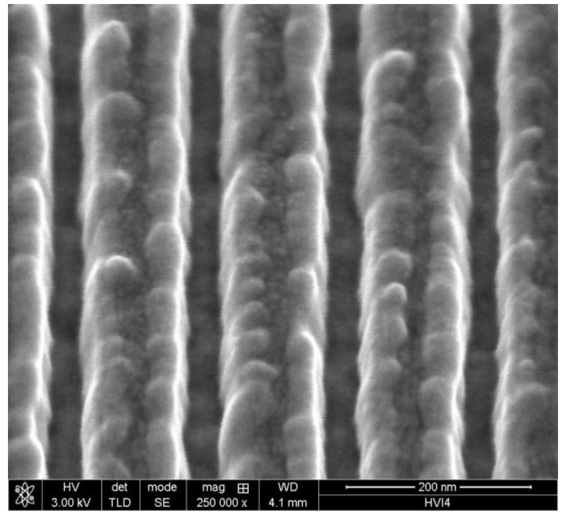
nanoantenna array: p=3µm, a=2µm, b=220nm; scale=1µm

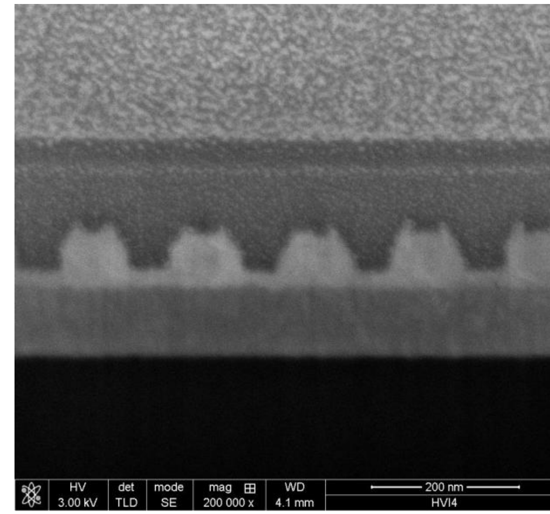


rect. pinhole array: p=100nm, dia.=40nm

Mask Patterns

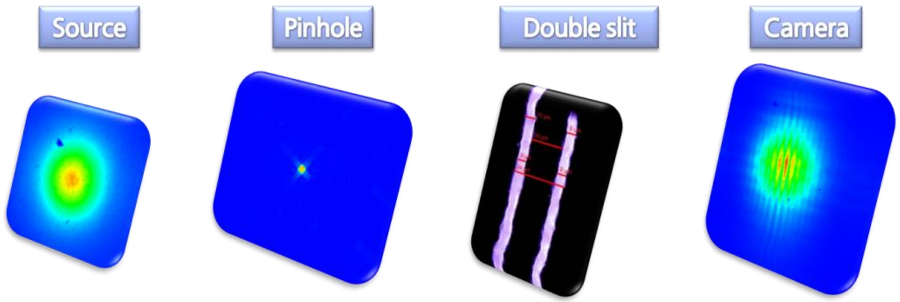


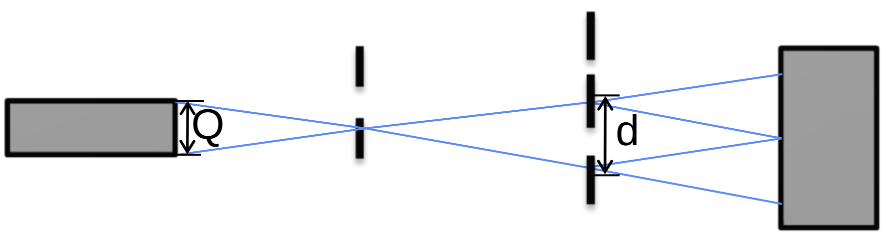




Ni redeposition during IBE limits the achievable resolution of the masks

Spatial coherence measurements

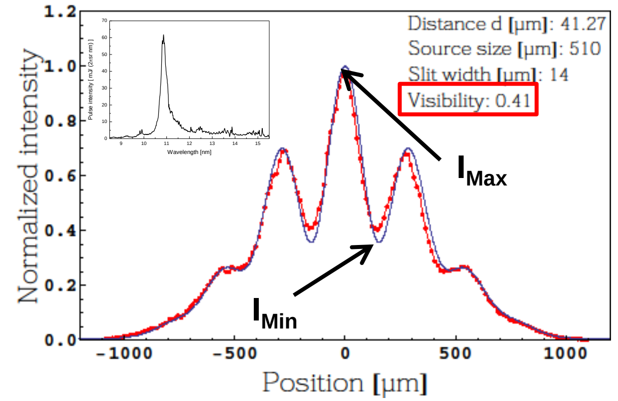


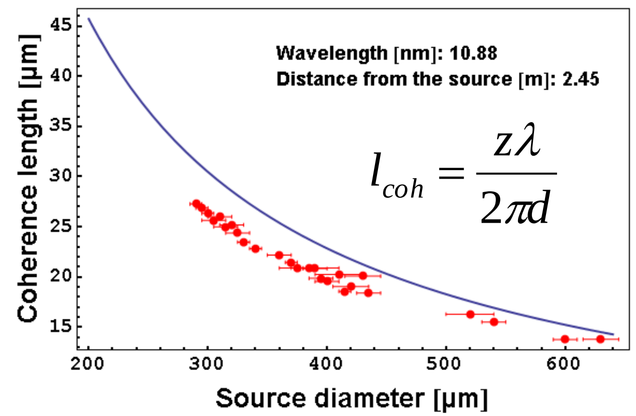


$$V = \frac{I_{Max}(d,Q) - I_{Min}(d,Q)}{I_{Max}(d,Q) + I_{Min}(d,Q)} = |\mu|$$

V : *Visibility*

μ : *Degree of Coherence*





Spatial coherence lengths up to 27 µm was measured

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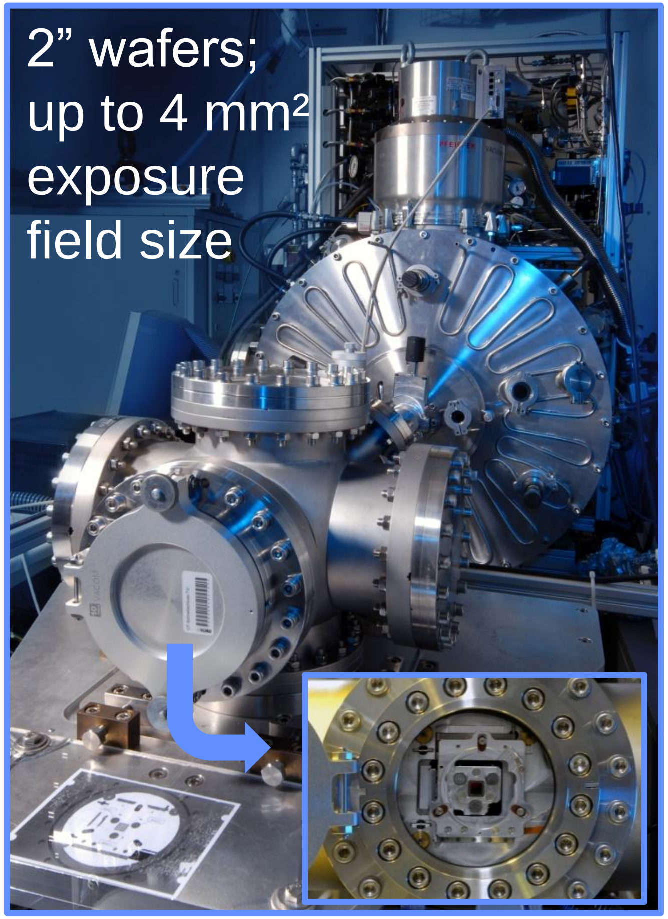
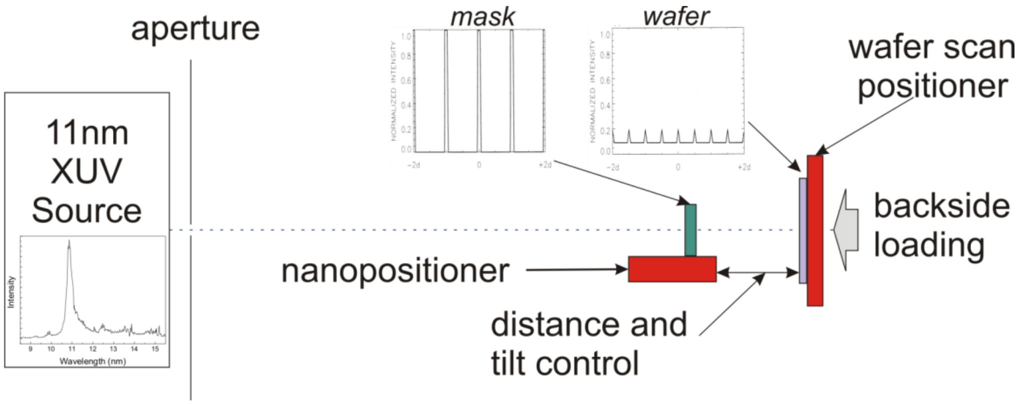
Exposure stage





- Wafer-mask control with nanometer precision
- Compact and rigid to minimize vibrations
- Minimum optical components to reduce power loss

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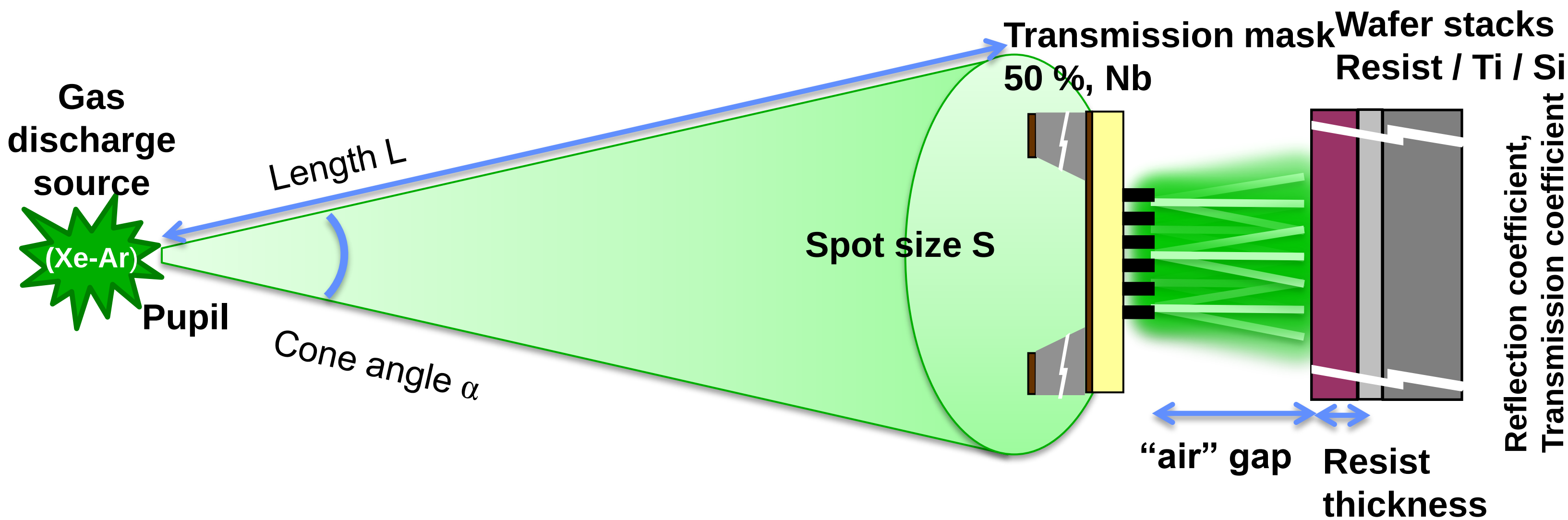
Lithography simulations (Dr. Litho)



❖ Simulation modules (→ Research area)

Source
- ✓ Wavelength
- ✓ Bandwidth
- ✓ Pupil shape
- ✓ Cone angle
- ✓ Polarization

Mask
- ✓ Absorber
- ✓ Transmittance
- ✓ Scalar diffraction models (Kirchhoff, RS I, II)
- ✓ Rigorous diffraction simulation

Resist
- ✓ Stack, Resist parameter (Dill ABC)
- ✓ Exposure time
- ✓ PEB time, temp. (Diffusion)
- ✓ Develop time (Mack parameter)
- ✓ Resist profile (Process windows)

Summary

• EUV Interference lithography is a powerful tool for cost efficient patterning of nanoscale periodic arrays

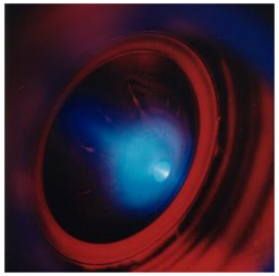
• Optimized high power gas discharge source can be effectively used as a source for EUV-IL

• Talbot lithography is the most efficient solution for nanopatterning with sources of limited coherence.

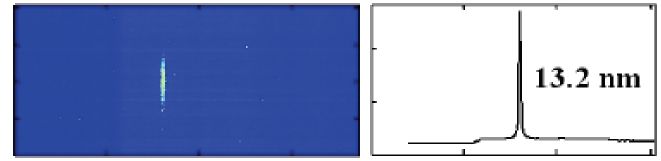
• Nb-based transmission masks can be used as an universal solution for interference lithography with wavelength between 6 and 15nm

•The resolutions down to sub-10nm are possible, limited by mask quality and resist performance

Summary and Outlook



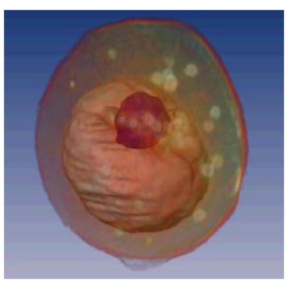
XUV plasma based sources
- new very efficient technology
- “Aachener Lampe” successfully used in EUVL & metrology



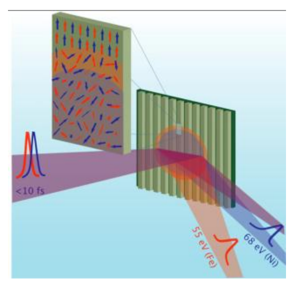
High brilliance metrology sources
- small emitting volume
- XUV lasers

future research challenges

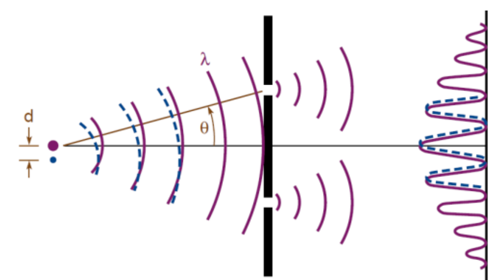
3d imaging
- combining of lateral and in-depth resolution
- cell nanotomography



Spectro-microscopy
- combining of spectral and lateral resolution
- magnetic domains



Coherence
- holography
- lens less imaging
- interference litho



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Matus Banyay, Sascha Brose, Serhiy Danylyuk, Carsten Dittberner, Ralf Freiberger, Johannes Hauck, Stefan Herbert, Peter Loosen, Aleksey Maryasov, Sammy Pissinger, Jochen Stollenwerk, …

ILT – EUV und Plasma Technology

Markus Benk, Klaus Bergmann, Manuel Bornhöfft, Michael Jansen, Felix Küpper, Willi Neff, Ralf Prümmer, Stefan Seiwert, Rafael Tadjer, …

Bruker ASC, Bergisch-Gladbach

Xtreme Technologies, Ushio group

Prof. David Attwood, University of California, Berkeley and Center for X-Ray Optics, Lawrence Berkeley National Laboratory

Thank you very much for your attention!